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Testing of an Epoxy Lining Material for Drinking Water Pipeline Rehabilitation

by

Sincy Modayil

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Environmental Engineering

Department of Civil and Environmental Engineering

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(Date thesis approved by committee)

ABSTRACT

The semi-structural strength of an epoxy lining material, Nitoline WP, was quantified using pressure tests. Sections of ductile-iron pipe with exposed lining areas of 1/4 in., 1/2 in. and 3/4 in. diameter were subjected to 120 psi water pressure. Results indicate that the epoxy lining sprayed at 2 mm (80 mils) thickness provided protection to the underlying corroded pipe with pits up to 3/4 in. diameter from further deterioration. The lining material at the standard thickness of 1 mm (40 mils) was shown to protect corroded areas up to 1/4 in. diameter and reduce red water problems. Field investigations were conducted to confirm that no chemicals of concern were leaching from the lining material into drinking water passing through the rehabilitated pipes. Water quality in the field met and surpassed current Canadian drinking water guidelines. Laboratory leaching tests, based on factorial experimental design, and water absorption tests were also conducted.

Dedication

I would like to dedicate this work to my dear husband

Jacob Modayil

for his patience and support

Acknowledgement

I would like to thank my thesis supervisor, Dr. Tong Yu for his guidance and advice throughout my research work. I would also like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for providing me with the Industrial Postgraduate Scholarship, in collaboration with EPCOR Water Services Inc. This thesis work would not have been possible without their combined support. Thanks are also due to staff and colleagues at the Environmental Engineering Department of the University of Alberta for their technical assistance. Thank you!

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1 Introduction

Pipeline networks that convey drinking water have come a long way since the wood-staves of the 18th century. Cast iron has proved to be a good pipe material that has served potable water piping needs for about a hundred years. However, the underground pipelines in most major cities in North America are beset with problems due to pipe age and corrosion. Continual and variable stresses on these pipes also worsen their condition, leading to pipe breaks. These issues are discussed in the following sections. Many methods have been used by utilities to cope with these problems including pipe replacement and rehabilitation. New techniques known as trenchless technologies are gaining popularity in the past two decades in underground pipe rehabilitation. The experience of the city of Edmonton with epoxy spray-lining of pipelines, which is a trenchless technology, forms the background to this research project.

1.1 Ageing infrastructure in North America

The construction of most central systems of Canadian water and wastewater infrastructure was started in the middle of the nineteenth century, around the same time as their start in Europe (Gohier, 2000). A major part of the Canadian infrastructure was built just after the Second World War and again in the 1970s, which is now in need of restoration. Cast iron has been used in modern water systems from the last 150 years and now ductile and cast iron together form the majority of water main pipelines in the United States (Ellison, 2001). The pipeline network constitutes about two-thirds to three-fourths of the assets of a drinking water distribution facility. The condition of the pipe network is especially important since the quality and pressure of supplied water has to be

maintained. Major rehabilitation and replacement projects are now being undertaken across North America. This situation is faced by all large North American cities since most were started at least 100 years ago and parts of their distribution system were put in place at that time. Pipes of this age are likely to suffer from problems such as internal corrosion, tuberculation, cracking and leakage. Some of these problems with old pipes, primarily made of cast iron, are discussed in the following section.

1.2 Corrosion of cast iron pipe

Due to its age, predominance and material properties, cast iron pipes undergo the majority of pipe breaks in the United States (Ellison, 2001). Unlined cast iron is prone to tuberculation, which refers to the encrustation of corrosion products and mineral deposits found within pipes.

Corrosion is defined as the "physicochemical interaction between a metal and its environment which results in changes in the properties of the metal" (Snoeyink and Wagner, 1996). The mechanism of metal corrosion is explained by the theory of electrochemical corrosion. The essential conditions for corrosion to occur are difference in electrical potential on regions on the metal surface, continuous metallic connection between the two regions and presence of an electrolyte solution. The difference in electrical potential causes one region to behave as an anode and an adjoining region to behave as a cathode, leading to oxidisation of the metal at the anode. Water is the electrolyte in the distribution system that allows movement of charged ions towards the oppositely charged regions and maintains electroneutrality.

The electrochemical reaction at the metal surface is represented as follows (Snoeyink and Wagner, 1996):

$$Me \leftrightarrow Me^{z+} + z\, e^-$$

where Me denotes the metal (iron) atom, Me^{z+} the metal ion, e^- the electrons lost and z the number of electrons. Equilibrium is rarely attained in distribution systems, since other ionic species take up the electrons in the place of the metal ion. The other corrosion-related reactions that occur simultaneously in the distribution system are:

$$2H^+ + 2e^- \leftrightarrow H_2$$

$$O_2 + 2H_2O + 4e^- \leftrightarrow 4OH^-$$

$$HOCl + 2e^- \leftrightarrow Cl^- + OH^-$$

These reactions indicate that pH influences the electrical potential that drives the corrosion reaction. The potential-pH diagram for the iron-water system at 25 °C indicates that at a high potential and a pH range of 7 to 8 (usual for drinking water), the ionic species Fe^{2+} or Fe^{3+} are the stable forms of iron (Snoeyink and Wagner, 1996). The specific mechanism of iron corrosion takes place in the following steps:

$$Fe + OH^- \rightarrow FeOH + e^-$$

$$FeOH \rightarrow FeOH^+ + e^-$$

$$FeOH^+ \rightarrow Fe^{2+} + OH^-$$

The metal loss is a result of chemical reactions, as metallic Fe is converted to ionic Fe^{2+} in solution. The reduction reaction for iron is dependent on pH, as is clear from the involvement of the OH^- ion in the above reactions.

Corrosion occurs in many forms including uniform, galvanic and localised (pitting) corrosion. Uniform corrosion is characterised by the shifting of anodic and cathodic sites on the metal surface, causing nearly consistent metal loss. Galvanic corrosion is initiated by the placement of different metals in contact with each other,

forming a corrosion cell arrangement. Localised corrosion (which includes pitting) occurs due to imperfections or high stress areas in the metal, which form the anode. This type of corrosion is fairly rapid compared to uniform corrosion since the same anodic dissolution is concentrated over a small area. The concentration of soluble species that participate in the electrochemical reaction (such as dissolved oxygen or hydrogen ions) may vary at different points in the electrolyte or the metal surface, resulting in what is known as concentration cell corrosion. This type of corrosion is seen underneath adhesions on metal surfaces (Snoeyink and Wagner, 1996). The primary effect of corrosion on the metallic pipe is to reduce its strength, which is further exacerbated by additional stresses placed on the pipe, as detailed in the next section.

1.3 Stresses on pipes and joints

Water mains in the distribution system are subjected to constant internal pressure and dead load from their own weight. They may also be subjected to live loads from traffic (Ellison, 2001). Beam bending and thermal stresses are other types of loads that can cause pipe failure. Beam bending of pipes occurs when buried pipes are subjected to deflection by soil movements, frost heaving, vehicular loads, etc. Thermal stresses lead to water main breaks seen frequently in the winter months. Pipes that are weakened by corrosion are more susceptible to failure.

Hoop stress in the pipe wall is caused by internal hydrostatic pressure in a pipe (Ellison, 2001). It is directly proportional to the pressure and pipe diameter and inversely proportional to wall thickness. Excessive hoop stress produces longitudinal cracks or splits in a pipe. Circumferential cracks also occur due to excessive hoop stress, but are generally seen in pipe failures caused by bending. In cold weather, axial stresses are

increased due to contraction in the ferrous pipe material. Standard pipe design takes into account hoop stress due to internal pressure, bending stresses and deflection due to soil loadings and traffic above ground (Bonds, 1990).

As soil exerts pressure around a pipe, effects are found in both longitudinal and transverse sections. Soil load variations, bedding imperfections and poorly supported 'bells' may cause uneven longitudinal loading on pipes (Prevost, 1990). A pipe can be considered as a beam that is also susceptible to transverse deformation. This deformation is redistributed along the pipe cross-section, overloading some parts and causing a bend. If this occurs at a joint between water mains, a leak could result. The transverse deformation is suppressed by passive reactions from soil, which supports the pipe on the sides. However, joints are not usually placed under roads with heavy traffic.

Buried pipes also experience pressure from soil compaction above them, soil displacement due to seismic occurrences and soil movement due to improper initial bedding and backfill. Other short-term pressure loads can also result from ground water changes and frost action. The rehabilitation technique chosen for an existing pipe must take into account both the internal and external pressures acting on the pipe. Some methods of pipeline rehabilitation are discussed in the following sections.

1.4 Rehabilitation vs. replacement

Rehabilitation of pipes is generally more economical than laying new pipe or open-cut replacement (Herbert, 1994). There are many criteria influencing the decision whether the pipeline is to be rehabilitated or replaced. One such criterion is the durability of the pipe as influenced by its age and material of construction. The frequency of damages occurring in the pipe can also influence this decision. Other factors are the

replacement of house connections due to renewal, road resurfacing and endangerment of other pipelines in the vicinity. These factors can significantly increase the cost of a replacement project. The cost is the single most important factor influencing the decision of rehabilitation over laying of new pipe. Modern construction methods such as trenchless technologies offer rehabilitation at lower costs. For example, the cost of pipe relining is about 66% lesser than laying new pipe for 80 to 200 mm diameter water mains (Herbert, 1994).

1.5 Trenchless technologies

Since the early 1980s the trend in underground pipeline installation has been to focus on repair, renovation and rehabilitation of existing infrastructure (Kramer et al., 1992). The density of activities above the underground pipelines emphasises the need for trenchless technology. The advantages of trenchless technology include cost savings, reduction in labour, and less disruption to the public (Kramer et al., 1992). Rehabilitation of pipelines may be divided into on-line replacement techniques and structural renovation techniques. On-line replacement involves bursting or excavation, which basically removes old pipe while simultaneously replacing with the new pipe. With this technique, the option of increasing capacity is also available. Structural renovation is employed to prolong the life and improve performance of existing pipe. In addition to improved flow characteristics and leak reduction, linings used in such renovation also offer structural integrity. The limitations to structural renovation include reduced cross-sectional area of pipe and questions about the performance of lining and the service life of renovated pipe.

Some popular techniques of structural renovation are conventional slip lining, modified slip lining and spraying. Standard types of pipe may be used in conventional slip lining wherein the new pipe is inserted into the existing pipe and the annular space filled with grouting materials (Kramer et al., 1992). Modified slip lining includes the techniques of soft-lining systems (also known as cured-in-place pipe). Manufacturers of soft-lining systems provide a permeable liner that is saturated with resins, placed into position within the old pipe and cured. Usually no grouting is required as the flexible liner is forced against the existing pipe walls. Soft-lining systems were initially developed for sewer systems, but were adopted for gas pipelines across Europe, Japan and the US. These methods have also been approved for potable water pipeline rehabilitation in the US. Spraying of lining systems provides a lining that may not provide structural reinforcement to the pipe. Specific liners that are structurally reinforced are effective in providing strength to man-entry size pipes. Two component epoxy resins and polyurethane systems are used in the rehabilitation of water and gas pipes. Cement-mortar systems have also been used for this purpose. A significant advantage of spray linings over the other techniques is that the lateral connections are not closed off, allowing faster return to service. Other lining techniques such as soft-linings generally require an expensive remote-control cutting operation after cure.

The economics of trenchless technology have been studied by many organisations. The results indicate that the costs are competitive with other replacement techniques. The costs involved in a project involving vital infrastructure takes into account the direct cost to the utility and contractor, indirect costs as in compensatory payments and environmental and social costs. The capital cost of the equipment may be

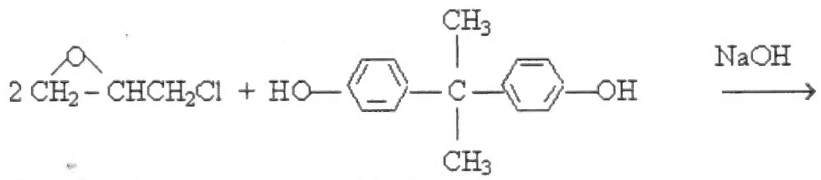
offset by increase in utilisation (Kramer et al., 1992). The need for future independent research to compare the structural performance of lining systems as well as their ability to withstand various loads in the long term has also been highlighted (Kramer et al., 1992). Most modern rehabilitation technologies also depend on the protective function of the old pipeline (Herbert, 1994). For this reason, the restored pipe enjoys the same life expectancy as newly laid pipes and is economical even if the pipe remains in operation only for 10 to 15 years. Lining manufacturers typically claim a lifetime of 50 years for pipe linings.

1.6 Epoxy spray lining

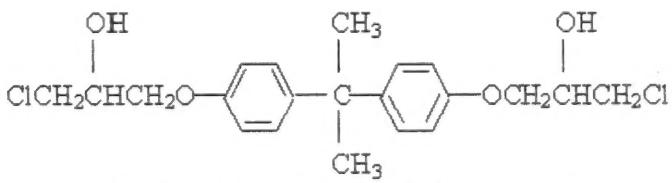
EPCOR Utilities Inc. is a publicly owned utility company that supplies drinking water, power and natural gas to the city of Edmonton and neighbouring communities in Alberta, Canada. The water services division of the company (EPCOR Water Services), hereinafter called EPCOR, provides water treatment, distribution and management to more than one million residents in western Canada (EPCOR, 2000). In the summer of 2001, EPCOR used a spray lining system in their water pipeline rehabilitation program. This program provided the background for the present research project. The spray lining material is a high-solids, low volatile organic compound (VOC) epoxy resin commercially known as Nitoline WP® manufactured by Fosroc Inc, US. The advantages of high solids (100% solids in this case) are the absence of volatile solvents and rapid cure time. The two-component resin is preheated in separate tanks, led through separate insulated hoses to the spray head, where the two components are mixed and discharged.

The spray system dispenses the preheated high viscosity product without using air to discharge the contents through the spray head.

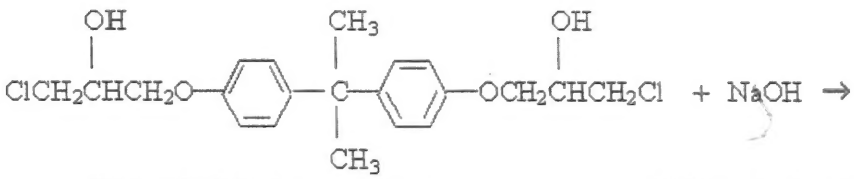
The Nitoline WP® product has been earlier used successfully in UK, New Zealand and the city of Chateguay in Canada. The epoxy resin in this product is the diglycidyl ether of bisphenol A (DGEBA). The spray coating consists of two parts: epoxy resin and hardener, which are packaged separately and mixed just before application. The epoxy resin part contains the reaction product of epichlorohydrin and bisphenol A as the major constituent, alkyl glycidyl ether used as a diluent and some inert filler (FOSROC, 2001). The hardener part consists of the curing agent trimethyl hexamethylene diamine, p-toluene sulphonic acid as an accelerator and some inert filler. The polymerisation reaction for the epoxy resin part is given in Figure 1 (Lee and Neville, 1967).

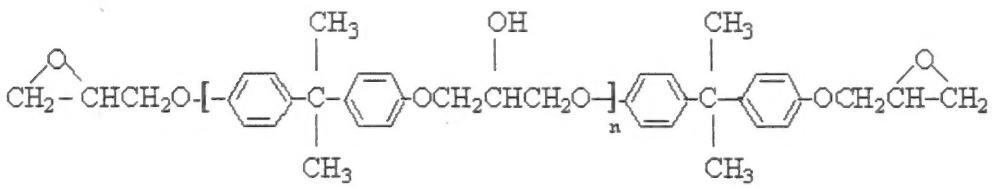


Epichlorohydrin **Bisphenol A**



Chlorohydrin intermediate (monomer)





Diglycidyl ether of bisphenol A (DGEBA)

Figure 1. Two-step polymerization reaction of epoxy resin

The DGEBA chain in Figure 1 gives the polymer structure of the epoxy resin part. Combination of this part with the amine curing agent (hardener) in the correct ratio results in the cross-linked epoxy lining material used in spray-lining pipes. The epoxy matrix is described as a mixture of very large macromolecular units made of crosslinked prepolymers (Alben et al., 1989).

1.7 Condition of pipelines in Edmonton

The water distribution system in Edmonton dates back to 1902 when cast iron pipe was the popular material in use. The city of Edmonton grew at a slow pace until the Second World War, but since 1946, it experienced rapid growth leading to increase in pipe installations. The cast iron pipes used at this time were spun cast, with a thinner pipe wall. In 1999, the distribution system had a total length of about 1850 miles, with the classification by pipe material as follows (Seargeant, 2002):

Table 1. Distribution system materials in Edmonton network

Pipe Material	Length (miles)	Percentage (%)
Asbestos cement	681	37
Cast iron	522	28
PVC	465	25
Steel	68	4
Concrete	66	4
Other	48	2

The metallic pipes were subjected to non-destructive testing to determine wall thickness. This would enable the utility to quantify the extent of corrosion and also check if the wall thickness is sufficient for a non-structural lining application. Non-destructive testing showed that the wall thickness in a corroding pipe can vary along its entire length (Seargeant, 2002), since the pipe is exposed to varying environments at different points. However, the tests determined that pipe walls were thick enough that they could be rehabilitated using the internal spray lining technique. EPCOR considered many spray coatings for rehabilitating the cast iron pipe. Cement mortar linings were considered an older technology associated with leached metals and lime under certain conditions and one that provided low control over mortar composition. On the other hand, epoxy-lining systems have been used in UK, Japan and other countries for many years with favourable results including increased hydraulic performance.

1.8 The red water problem

A frequently occurring problem resulting from internal corrosion of cast-iron pipes is the phenomenon of red water. Internal corrosion rarely leads to pipe breaks or failure since protective scales are formed at the surface, which subsequently reduces the rate of corrosion. However, red water is still an aesthetic issue that generates customer

complaints. Red water is caused by ferric hydroxide flocs in water, which may be triggered by sudden changes in water quality such as chloride and sulphate content. The mechanism of floc formation is detailed as the oxidisation of ferrous ions in the bulk solution and precipitation of the resulting ferric hydroxide. These ferrous ions may have been formed at the pipe surface or within the corrosion scales and migrated to the bulk phase by diffusion (Benjamin et al., 1996). Empirical evidence suggests that the formation of protective scales does not influence the formation of red water. It is reported that smaller pipes generally have this problem, as the iron concentration accumulated may be higher especially during periods of no water flow through the pipe. The iron release from the pipe walls has been found to depend on pH, carbonic acid concentration, dissolved oxygen and the salt content of the water.

The Kuch mechanism explains the formation of red water even in the absence of dissolved oxygen, in systems subject to frequent and alternating periods of flow and stagnation (Benjamin et al., 1996). In periods of flow, corrosion rates depend directly on the dissolved oxygen content of the water and oxygen diffusion through the scale is the rate-limiting step for corrosion. However, during periods of stagnation, the ferric oxides in the scale layer act as oxidants in the absence of oxygen and are themselves reduced to ferrous compounds. The corrosion reactions proposed during stagnation are as follows:

At pipe wall: $Fe \leftrightarrow Fe^{2+} + 2e^-$

Within scales: $2FeOOH_{(s)} + 2H^+ + 2e^- \leftrightarrow 2Fe^{2+} + 4OH^-$

The Fe^{2+} ions that are produced may precipitate or move out of the scale layer into the bulk water, where they are oxidised into ferric hydroxide flocs resulting in red water.

1.9 Use of epoxy lining in 2001

A particular older area of Edmonton had a history of red water complaints stemming from corrosion of cast iron mains. Although the phenomenon of red water is primarily an aesthetic issue, it is still an indication of underlying conditions. To overcome this problem, EPCOR decided to line the cast-iron pipes internally with the epoxy coating Nitoline WP®. About 174 ft of 6-in. diameter pipe and 2510 ft of 8-in. water mains were lined with the epoxy material in the first phase in July 2001. In Oct 2001, a second phase of lining was carried out, when another 482 ft of 6-in. pipe and 1785 ft of 8-in. mains were epoxy-lined.

The objectives of this work were to evaluate the semi-structural strength offered by the epoxy lining and to measure the amount of regulated chemicals that may leach into water. Semi-structural strength is defined here as the ability of a lining material to bridge over cracks and pits and protect corroded pipe from further deterioration, using the strength of the host pipe. Water quality tests including residual chlorine, turbidity, UV_{254} absorbance and odour tests were also part of the testing regimen for drinking water flowing through the epoxy-lined pipes. The scope of chemical detection was limited to testing for volatile and semi-volatile compounds that are currently or have the potential to be, regulated in Canada for drinking water.

2. Literature Review

2.1 Use of internal spray-linings for water mains rehabilitation

A survey was conducted to identify the major spray lining materials used in water main rehabilitation in North America. For this purpose, an initial Internet search was performed, followed by a telephone survey of the utilities thus identified. The survey questions varied according to the material used in rehabilitation. Thus the survey questions were as follows:

1. Do you have previous experience with cement-mortar/epoxy lining?
2. If so, did you have any problems with it?
3. Have you considered epoxy/cement-mortar lining?
4. How many metres of pipe have been lined so far using cement-mortar/epoxy lining?

Based on the responses to these questions and vendor case histories, information about rehabilitation materials across various municipalities in Canada and the United States were collected and are provided below.

The Region of Halton, Ontario, had started a cast iron water main replacement program in 1997 to deal with rusty water problems (Regional Municipality of Halton, 2001). This water was not detrimental to public health, but contaminated plumbing fixtures, stained laundry and the presence of carbuncles reduced fire fighting capabilities. The pipe replacement program follows cement-mortar lining of structurally sound pipes, which commenced in 1993 in the Oakville area. The remaining pipes are so severely deteriorated that cement-mortar lining is not considered viable for them. Approximately $9.4 million is assigned to replace 27200 metres of old cast iron pipe. Other water main rehabilitation techniques used earlier by the Municipality of Halton were pipe bursting and epoxy lining (Ellis, 2000).

The Los Angeles Department of Water Services is the largest municipally owned utility in the United States, serving a population of about 3.8 million (LADWP, 1996). The Department has used cement-mortar lining to rehabilitate about 850 miles of old cast iron water mains as of 1996. This project is expected to continue until 2006 with an annual expenditure of $34 million. The Department has about 70 years of experience with cement-mortar lining and has not faced problems with its usage in potable pipes (McLachlan, 2003). Epoxy coatings are used in sections where high velocity is expected, but is not applied on a larger scale due to uncertainty about its service life.

The Washington Suburban Sanitary Commission proposes to clean and line water mains in the Suitland and Forestville area in 2003 (WSSC, 2001). The Commission for the past 30 years has used cement-mortar lining in their distribution system. They are also interested in exploring other lining materials that can provide structural strength and are currently planning an epoxy demonstration (Senesie, 2002).

The City of Waterloo, Ontario, has begun a lining program to apply cement-mortar lining in about 52 kms of iron pipe between 2002 and 2005 (City of Waterloo, 2002). It will also replace 5 kms of iron pipe in the areas reporting the most discoloured water problems. As part of this overall rehabilitation program, about 6 km of pipe has been lined by December 2002, with 18 km planned for the year 2003. There were no problems reported with the cement lining known as WWAC602-00 or the lining process so far (Iddifcombe, 2002).

The City of Burnaby, British Columbia, has launched an epoxy-lining program in 2002, to line about 400 m of cast iron pipe in the Marine Drive area (City of Burnaby, 2002). However, a few problems such as unexpected delays and the resulting increase in

costs were recorded (Ensing, 2002). Some water mains are also being newly constructed as part of this rehabilitation program.

The City of Toronto, Ontario, has used cement-mortar lining as part of its preventative maintenance program (City of Toronto, 2002). Cement lining is used to reduce instances of discoloured water, improve hydraulic capacity for buildings and fire fighting. The process involves the removal of rust build-up inside the old mains and internal lining with cement mortar.

The Massachusetts Water Resources Authority operates about 15 miles of unlined cast iron mains in the Boston Low Service Network (MWRA, 2002). These cast iron mains were laid between 1848 and 1908, now forming a source of main breaks, non-operating valves and corrosion products in water. Since 1999, the Authority has begun to rehabilitate large water pipelines in the Brookline area and smaller portions of pipe in Brighton. This includes for the most part, cleaning and internal lining with cement-mortar lining inside sections of existing 20 to 48-inch pipe. Large valves that are no longer operable are being replaced as well. The cost of the 10-mile pipeline construction work included in this contract is $14 million. Epoxy lining has been used for speciality applications such as venturis and valves, but not for the pipes themselves, due to earlier unsatisfactory experiences with the lining (Tes-Smargiassi, 2002). About 15% to 18% of the total distribution system has been lined or replaced in the past 30 years.

In response to discoloured water complaints during the last few years in the Thomas Avenue area, the Minneapolis Water Department has undertaken a cement-mortar lining project for water mains (City of Minneapolis, 2002). A major part of the water mains in Minneapolis is over 50 years old and unlined cast iron. The Water

Department has decided to line at the same time all the pipes throughout the Armatage neighbourhood as well as a few blocks of the Fulton and Lynnhurst neighbourhoods. During this process, many fire hydrants and valves that are past their expected life cycle will be replaced and new water main pipes will be installed in two blocks. About 9 miles of pipe were cleaned and lined between July and October 2002.

A $4.35 million project has been undertaken by the Middlesex Water Company in New Jersey to clean and cement-line water mains (Discharger, 1999). Other water mains projects in the State of New Jersey include a $915,920 clean-and-line project in the City of Brigantine and a $464,272 replacement project for water mains in Westville Borough.

Dakota Pipelining Systems has cleaned and lined nearly 700,000 ft of water mains in the City of Sioux Falls, South Dakota, since 1990 (Dakota Pipelining, 1999). The lining process undertaken to rehabilitate the ageing infrastructure in the city was completed in May 1998. A significant increase in carrying capacity of pipes was noted after this work. The cost savings when compared with pipe replacement were also found to be substantial.

United Water New Rochelle (UWNR) operates over 400 miles of water mains in Westchester County, north of New York City. Water main rehabilitation programs started by UWNR include cleaning and cement-mortar lining of existing cast iron water mains that had been in service for approximately 100 years. About 12,000 ft of 8" cast iron water main and 4,700 ft of 16" cast iron water main is proposed to be lined under a contract with Buck, Seifert & Jost, Inc (BS&J, 2001).

The Region of Ottawa-Carleton, Ontario, in June 2000 proposed a $391,753 clean and epoxy line program (Region of Ottawa-Carleton, 2000). The water distribution

system in the region contains about 500 km of unlined cast iron pipe installed between 1874 and 1959. The replacement costs of these pipes was estimated to exceed $300 million. Analysis of break histories in the cast iron pipes, installed between 1950 and 1959, indicate that these pipes is still structurally sound and do not require immediate replacement. Epoxy lining has proven to be a cost-effective rehabilitation method with an expected design life of 40 to 50 years. In September 1998, the Region successfully completed its first cleaning and epoxy-lining project of approximately 780 m of unlined cast iron water mains in the Village of Rockcliffe, to resolve a red water problem. Following this experience, the epoxy lining technology was used in an expanded cleaning and lining contract in 1999. This contract involved the cleaning and epoxy lining of approximately 3,600 meters of existing 152 mm and 203 mm water mains on six streets located in the Copeland Park, Nepean area, by June 2000. A budget allocation of $1,400,000 was identified for the 2000 cleaning and lining component, with a proposed budget allocation of $1,500,000 for 2001.

The Boston Water and Sewer Commission has used cement-mortar lining in its rehabilitation programs, since it is considered a proven technique. About 50% of the total distribution system has been rehabilitated using this method, with no problems reported so far (Letch, 2002).

It is evident from the above information that trenchless technologies such as internal spray lining of pipes are gaining popularity in North America. However, its application for potable water tanks and reservoirs are not taken into account in this study, which focuses on pipelines only. To summarise, some major cities or municipalities in

North America that recently used a spray lining technique for their drinking water pipelines were identified and are listed in Table 2 below.

Table 2. Utilities that used spray-lining for drinking water system rehabilitation

City/Municipality	Lining Material
Regional Municipality of Halton, ON, Canada	Cement mortar
Regional Municipality of Halton, ON, Canada	Epoxy
Los Angeles, CA	Cement mortar
Washington Suburban Sanitary Commission, MD	Cement mortar
Waterloo, ON, Canada	Cement mortar
Arlington County, VA	Cement mortar
Toronto, ON, Canada	Cement mortar
Massachusetts Water Resources Authority, MA	Cement mortar
Minneapolis, MN	Cement mortar
Middlesex Water Company, NJ	Cement mortar
New York, NY	Polyurethane
Sioux Falls, SD	Cement mortar
Moncton, NB, Canada	Epoxy
New Rochelle, NY	Cement mortar
Burnaby, BC, Canada	Epoxy
Region of Ottawa-Carleton, ON, Canada	Epoxy

Cement-mortar lining was used for internal spray lining in most cities reviewed, due to its long use hitherto in distribution systems and its proven durability. However, reports of leaching of metals and other chemicals from cement-mortar linings should restrict its continued use.

2.2 Pressure tests

Pressure tests have generally been used to determine the structural strength and integrity of pipes. The standard C600-93 as published by the American National Standards Institute and American Water Works Association outlines a standard hydrostatic test that is used for the installation of ductile-iron water mains and appurtenances (ANSI/AWWA, 1993). Few structural tests of pipe coatings have been reported in literature. However, some studies have attempted to use pressure tests to determine the strength of pipe linings (Bakeer et al., 1999; Luk, 2001; Seargeant, 2001). Structurally reinforced linings have been tested using external hydrostatic pressure and negative internal pressure as discussed in the following sections.

2.2.1 Hydrostatic pressure testing

A study by Chemtron Technology and Engineering, California, US investigated the use of epoxy lining in steel pipe to protect holes of size 1/16 in. to 3 in. diameter (Seargeant, 2001). Internal hydrostatic pressure of 2000 psi was applied unless the lining failed. Epoxy lining in holes larger than 3/4 in. diameter failed to withstand the hydrostatic pressure and ruptured.

In a study on trenchless wastewater pipe repairs with epoxy coating, researchers at the University of Texas, Austin, used a watertightness or leakage test to estimate the seal provided by the coating on concrete (Bauhan et al., 1997). The test was used to evaluate the structural strength of the repairs, by calculating the leakage through the cracks when pressure was applied. Large variations were found in leak rates per meter of crack between the samples. They also found that the bonding of epoxy to concrete

depended most on the surface conditions and failures were caused due to dusty surfaces and calcareous aggregates. Field samples with real defects were repaired, excavated and used in their tests. The specimens were subjected to internal hydrostatic pressure to test for water-tightness. Tension was applied along the pipe axis to test for bond strength in repaired specimens.

A study on plastic liners (Bakeer et al., 1999) indicated that short-term tests, that is pressure testing of liners until failure, tended to overestimate the buckling resistance of the liner. However, the short-term tests are valuable in establishing the basis for long term tests. A factor of safety is applied to the collapse pressure found from a short-term test to determine the design pressure for long-term tests of 10,000 hours or so.

Pressure tests were used to study the strength of reinforced cement-mortar lining by applying negative pressure to a lined pipe until lining failure (Luk, 2001). The rupture pressure thus determined was said to represent the field tensile strength of the lining.

2.2.2 Joints testing

The durability of a pipeline is largely dependent on the durability of its joints. Rubber joint rings used since the 1920s have performed with reasonable success in maintaining leak-proof joints (Klein and Rancombe, 1985). However, many of these are now showing signs of microbiological degradation with loss of rubber content. This may cause leaks at joints and migration of loose particles, which may be prevented by the sealing effect of interior pipe lining. Also, lead joints have been used extensively in the past at the junction of pipe sections. This creates a potential health hazard as the lead may be leached into water by continuos exposure (Luk, 2001). It is supposed that the use of

epoxy lining would likely minimise the leaching problem by sealing these joints. Thus a need to study the flexibility and sealability of epoxy lining at these joints is identified. Slip joints are generally used in water distribution lines, which consist of a spigot inserted into a bell, held by compressing a rubber gasket (Mueller, 1983). Unanticipated thrust could easily disassemble these joints. Also known as push-on joints, these allow a certain amount of deflection and longitudinal displacement, while maintaining hydrostatic seal (Bonds, 1990). This flexibility is useful in preventing the accumulation of excessive bending stress.

With time, soil around buried pipes tends to settle and exert pressure against them (Petroff, 1990). Soil exhibits viscoelastic behaviour, that is, its acts as a combination of a viscous liquid and an elastic solid. It is generally represented as the combination of spring (elastic) and dashpot (viscous) elements, where the spring reaction is independent of time and proportional to the applied load. The dashpot element also reacts in proportion to the applied load, but behaves like a leaky piston, thus decreasing with time. The viscous behaviour leads to recoverable and non-recoverable deformations. This behaviour of soil must be taken into account during pipe design, as it could affect the long-term performance of buried pipe.

2.3 Field leaching tests

High levels of tetrachloroethylene (TCE) were reported to have leached from vinyl-toluene lined asbestos-cement pipe at a location in Newport, Rhode Island, US (Larson et al., 1983). The service line into Brenton Point State Park was a lined pipe, which was also a dead end. Lower levels of TCE were also reported in other areas of

Newport, associated with lined asbestos-cement pipe. Flushing and bleeding of water mains reduced the problem. It was found that longer cure time for the lining resulted in lower residuals of TCE. The manufacture of lined asbestos-cement pipe has since been discontinued in New England, US.

In 1989, field studies were carried out by researchers at the New York State Department of Health researchers on water storage tanks internally coated with epoxy lining. Water samples were collected for analysis of trihalomethanes and volatile aromatic and ketone solvents (Alben et al., 1989).

2.4 Laboratory leaching tests

An early study on the migration of vinyl chloride monomer from polyvinyl chloride pipes that was conducted in Japan used deionized water at different pH levels as extracting solution (Ando and Sayato, 1984). Since the monomer was undetectable using a pipe section, it was cut up into pieces to allow better contact surface area. About 50 ppm of vinyl chloride monomer was determined to have migrated from the pipe during the 96-hour test. The test set-up used 10-mL serum vials sealed with an aluminium cap lined with Teflon septa. The vials were filled to overflowing to remove air space, to prevent escape of volatile compounds. The solutions were tested using a gas chromatograph and the reaction products of the monomer with chlorine were also studied. Chlorine, a commonly used disinfectant, formed different reaction products with the monomer under different pH conditions. An 1981 study on the migration of vinyl chloride from PVC pipe also noted that pipes that were aged in air for a longer time (60, 120 days, as compared to 30 days) before putting into service showed lower

concentrations of vinyl chloride in the contained water. The maximum holding time for water in these pipes was three days (Vinson and Banzer, 1981).

A study of laboratory test procedures (Packham, 1971) reveals some important facts about leaching of lead stabilizers from polyvinyl chloride pipe. Continuous flow extractions were found to yield smaller amounts of lead compared to empty-and-refill techniques. The author also observed that the most valid test of leachability of stabilizer from the pipe would involve an extraction with water of the same composition as will be conveyed finally in the pipe. The use of sodium bicarbonate solution was recommended over carbon dioxide solutions to represent aggressive natural waters. Flushing of pipe as a preliminary step in the test procedure resulted in lower extraction levels. But the amount extracted otherwise may not have any bearing to field conditions. Therefore, the leaching test may be used to compare different materials, but cannot be used to predict the amount of leaching in practice. The leaching test carried out was a static test and the use of agitation was recommended for future tests.

A similar study was carried out to study the leaching of PVC pipe additives using deionized water (Dietz et al., 1979). Static leaching tests were performed at two temperatures, 25°C and 50°C, by immersing 14 cm pipe lengths in 2 litres of deionized water contained in a sealed glass jar. After a two-week period, 100 mL samples were removed for analysis and subsequent analyses were corrected for the dilution effect of fresh deionized water added each time. Trace metal analyses on the samples showed that calcium, tin and magnesium were extracted from the pipes. The general trend of leaching of these metals showed that maximum extraction levels were reached in about 2 weeks, after which the extraction values remained constant.

Petroleum-asphalt coatings on ductile iron pipe were reported (Miller et al., 1982) to contribute less than 15 ppb of polynuclear aromatic hydrocarbons (PAHs), which is about 20 times lower than the then-applicable WHO standard of 200 ppb for PAHs in drinking water. Gas chromatography-mass spectroscopy (GS-MS) was used to analyse the high purity contact water used in these experiments. Freshly coated pipes were connected in a recirculating water system to maximize leaching and maintain accelerated exposure conditions. The pipe was cured to allow evaporation of volatile organic compounds and flushed with tap water for about 4 minutes.

Cement-mortar linings were found to release regulated metals into contact water in a recent laboratory study (Guo et al., 1998). Freshly coated pipes were disinfected with chlorinated water and flushed. The pipes were then filled with tap water and maintained in a static pressurized condition for about 2 weeks. Analysis of samples during this time showed a significant amount of barium, cadmium and chromium release in this first fill, the maximum being about 20% of the drinking water standards. The metal concentrations in all cases was found to increase and then decrease slowly.

Studies were conducted on various lining materials including epoxy lining to tests for changes in water quality by recording pH, turbidity, iron content and alkalinity (Luk, 2001). These tests used parts of an old pipeline that were lined in-situ and then dug out. Epoxy lined sections were reported to exhibit a marked increase in turbidity. The experiments did not reproduce the flushing effect of the field distribution system, although both agitated and undisturbed stagnant water was used. Details about how the water was agitated was not provided in the paper.

A comprehensive study was carried out in 1989 on the leachate of five organic coating materials used in potable water distribution system, including an epoxy coating (Alben et al., 1989). By measuring the increase in concentration per time interval, the researchers demonstrated that the rate of leaching decreased with time as a simple exponential. Diffusion of the compounds was assumed to obey Fick's first law of diffusion, where flux is directly proportional to the change in concentration per unit distance from the coating-substrate interface. Majority of the compounds found to leach from the tested epoxy coating were the solvents methyl isobutyl ketone, o-, m-, and p-xylene. They also found some unknown compounds originating from the hardener and chlorination products of the solvents. The rates of leaching were found to be 40 to 187 μg/L-day initially, dropping to 8 to 37 μg/L-day after a month. The water used in the experiments was tap water passed through a fixed bed of granular activated carbon. Steel panels were sprayed with epoxy, cured and immersed in water. An open static headspace was allowed in the containers used for test panel immersion, as per usual storage tank operation. The volume to surface ratio used was 0.164 m^3/m^2.

From the above literature, two major trends may be seen in leaching tests on pipes. The older experiments relied on static tests using water as extractant and did not use a flushing procedure prior to start of experiment. The later experiments also used water as extractant, but used recirculation or agitation to maximize leaching and the flushing procedure in some cases.

2.5 Water absorption tests

It is known that all polymer coatings are permeable to water to some extent, depending upon the coating characteristics, interface between metal and coating, etc. Studies have found that Fick's law of difusion is valid in the initial stages of water absorption through micropores in the coating structure (Miskovic-Stankovic et al., 1999). The major mode of coating failure is due to blistering, which is caused by osmotic pressure from dissolved corrosion products. Impurities at the metal-coating interface may also include hydrophilic solvents and salt residues.

Some water permeability is required to prevent this blistering, which would otherwise result in damage to the coating (van Westing et al., 1994). It was also noted that the water uptake affected the polymer in the coating resulting in swelling, shown by change in its dielectric properties. In a study on epoxy-coated steel used for reinforcing concrete, it was found that the epoxy coating debonded from the steel due to water and chloride penetration to the metal-coating interface, resulting in corrosion under the coating (Weyers et al., 1998). The factors influencing adhesion loss were identified as the type and concentration of ions in water, temperature, amount of free water in the concrete and the number of coating defects. In this particular case, the reinforced concrete was not able to extend service life of structures (bridge decks) beyond 5 percent.

Water absorption by fibre-reinforced polyurethane, a structural lining, was found to reduce its tensile strength (Grami et al., 1995). It also resulted in cracks, which were found to be the predominant mode of failure. The rate of degradation was lesser at lower temperatures (20°C versus 95°C). Specimens were tested under bending stress.

The water absorption behaviour initially follows Fick's law of diffusion which is enhanced by temperature (Ellyin and Rohrbacher, 2000). Moisture absorption by weight, M(t) of a specimen is given by the equation:

$$M(t) = \left[\frac{m(t) - m_{dry}}{m_{dry}} \right] \times 100 \qquad \text{Equation 1}$$

where $m(t)$ is the current mass of the specimen and m_{dry} is the initial dry mass.

The ASTM Standard D570–98 indicates that the moisture absorption of plastics affects such properties as mechanical strength, appearance and dimensions. Diffusion of liquids into polymers is a function of the square root of time and the time to saturation depends strongly on specimen thickness. Blisters may form under intact coatings by diffusion of water vapour and oxygen (Geenen et al., 1990). Water may accumulate at the coating-substrate interface forming monolayers of condensed water. The availability of anodic (metal) and cathodic species (water and oxygen) could initiate a corrosion reaction beneath the coating and delamination from the substrate.

3. Materials and Methods

3.1 Pressure tests

The following sections describe the experimental set-up used, methodology and the detailed test procedures for both single pipe specimens and pipe joints.

3.1.1 Testing of pipe sections

The experimental systems used 2 ft. (0.6 m) long sections of 8 in. (200 mm) diameter Class 150 ductile-iron pipe. Each section bore three similar sized holes positioned along a straight line on the pipe and separated by a distance of 6 in. (150 mm) approximately. The sizes of holes drilled were 3/4 in. (20 mm), 1/2 in. (12 mm) and 1/4 in. (6 mm) each in diameter. These holes were plugged with putty and a smooth finish was formed on the inner and outer pipe surface. The pipe sections were then internally lined with the epoxy lining material under study and allowed to cure. The standard thickness of 1mm epoxy lining material was obtained by spray lining once and the double thickness of 2 mm was obtained by spray lining twice, with a 24-hour cure period between coats.

The diameters of exposed areas were chosen to represent corroded pits of similar size found in old cast iron pipes. The putty signifies a thinner pit wall that may contain products of corrosion. It is generally known that the corrosion products do not have the strength of the original metal. Pipes with holes that go through the pipe wall are not conducive to spray lining.

The water was then pumped into the sections using a 3000 psi Jerrycan hand pump that has a discharge stroke volume of 11.96 mL. Before application of the test pressure,

air was completely expelled from the pipe section using a pressure release valve. The water in the sections was brought up to pressure and maintained for 2 hours at 120±5 psi. The pressure was increased in small increments (1 psi/second) and monitored using a calibrated pressure gauge with minimum gradations of 5 psi. The pipe sections were tested in duplicate and also triplicate when necessary. The end of the experiment was decided to be 2 hours at test pressure or epoxy lining rupture at the holes, whichever came first. The pressure gauge used in the experiments was calibrated with a sensitivity of 5 psi, accuracy of 0.5% and range of 0-200 psi.

3.1.1.1 Experimental methodology

A study conducted by Chemtron Technology and Engineering investigated the use of epoxy lining in steel pipe to protect holes of size 1/16 in. to 3 in. diameter (Seargeant, 2001). The results indicated that a particular epoxy coating, TR-2000, was able to withstand hydrostatic pressure of upto 2000 psi when the epoxy-covered holes in the steel pipe were of less than 3/4 in. diameter. The pressure was applied until 2000 psi was reached or when the lining ruptured.

In the present study, a similar technique was used to measure the semi-structural strength enhancement provided by the Nitoline epoxy lining. Semi-structural strength is defined here as the ability to bridge over small cracks and holes and protect underlying material utilizing the strength of adjacent material. However, the test pressure was planned to be maintained at 120 psi for 2 hours as opposed to 2000 psi. The reason for choosing a lower pressure was that the pipe to be used in the test was Class 150 ductile iron pipe and not steel pipe. Although there are no standard procedures for this particular

type of hydrostatic testing, ANSI/AWWA C600-93, which outlines a standard hydrostatic test for the installation of ductile-iron water mains (ANSI/AWWA, 1993), was followed whenever possible. The hydrostatic pressure was to be maintained for 2 hours at 1.25 times the working pressure in the system, which is usually about 80 psi in the Edmonton drinking water distribution system. The size of holes was chosen to be 1/4 in., 1/2 in. and 3/4 in. as limited by the earlier finding.

The length of the pipe sections was selected to satisfy the criterion for effective length of a cylindrical shell. This criterion is used in order that a load at one location does not affect another location. This effective length L_{eff}, where the effects fade out to 0.19% of the original magnitude, is given by (Krishnamachari, 1993) in the following equation:

$$L_{eff} = \frac{2\pi\sqrt{R_m t}}{3\left(1-\nu^2\right)^{0.25}} \quad \text{in mm} \qquad (1)$$

where t = thickness of cylinder, mm

R_m = midsurface radius (nominal radius + half the cylinder thickness), mm

ν = Poisson's ratio of the material; a value of 0.35 is assumed since it varies within a narrow range.

Thus, the following rule of thumb is generated:

$$L_{eff} = 4.933\sqrt{R_m t} \qquad (2)$$

Using the dimensions of the ductile iron pipe under study, it was found that the effective length by equation (2) was about 12.9 cm. Therefore it was decided that in the experiments, the holes to be covered with epoxy lining material will be placed at least 15 cm (6 in.) apart.

The length of the pipe sections also satisfies another rule of thumb that the length-to-diameter ratio must be at least 3:1 to reduce end effects (Ellyin, 2001). Ideally the ratio should be about 10:1 to completely eliminate end effects (Bakeer et al., 1999).

3.1.1.2 Test Procedure

The experimental set-up for pressure tests of pipe sections is shown in Figure 2. The procedure of pressure testing is detailed as follows:

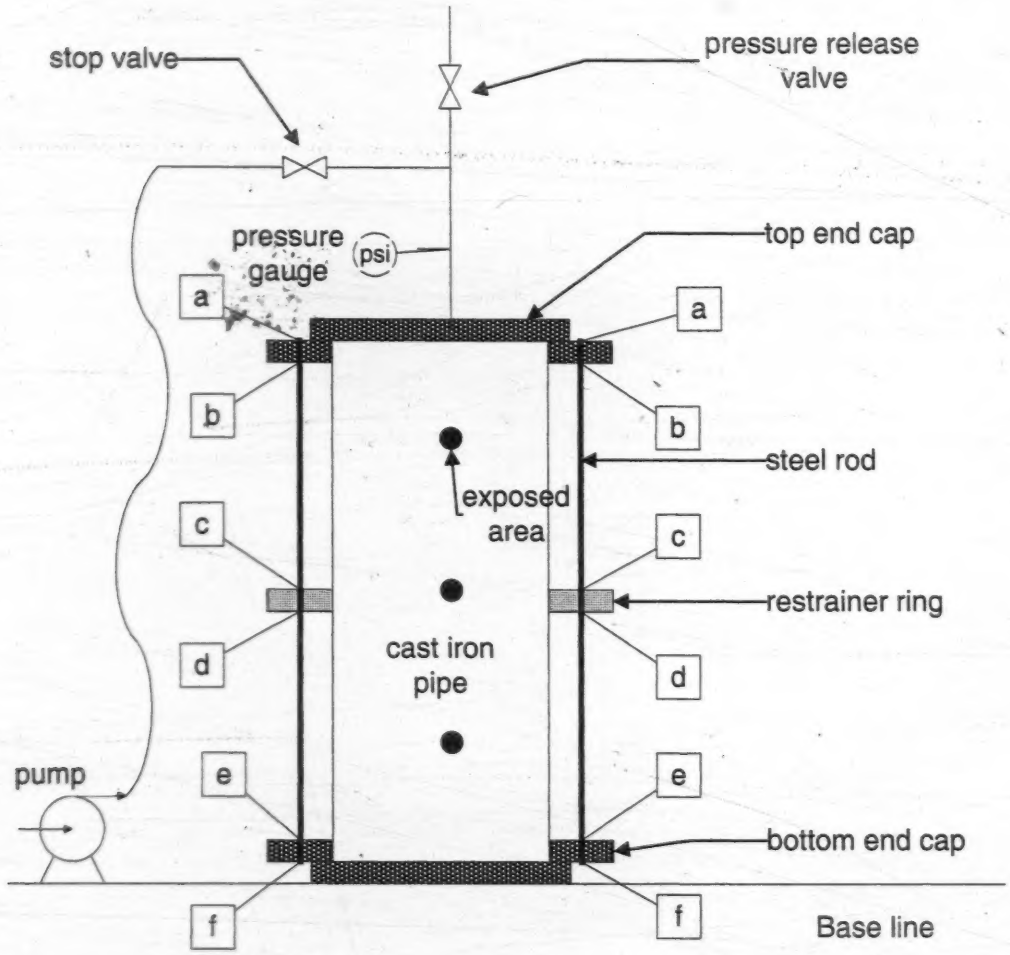


Figure 2. Experimental set-up for pressure tests of pipe sections

(1) The rubber O-ring (not visible in Figure 2) is fitted into position inside the bottom and top end-caps.

(2) Steel nuts labelled *e* on either side are first put on steel rods and passed through the slots in the bottom end-cap.

(3) The nuts labelled *f* are then put on and the end-cap is tightened between these adjacent nuts.

(4) The nuts named *d* are next added onto the steel rods such that they are well below the middle hole in the pipe section.

(5) The restrainer ring is lowered on to the rods in place, down to the level determined by the nuts that are labelled *d*.

(6) Using a level indicator, the screws on the restrainer ring are tightened to the pipe section such that the ring is parallel to the ground. This makes sure that the pipe is placed perpendicular to the base line.

(7) The nuts labelled *d* are now loosened, while the nuts labelled *c* are used to force the pipe section downward into the bottom end-cap.

(8) When the pipe is not able to move any further down, it is filled with water to about 5 inches below the brim. At this time, any leaks noticed in the bottom end-cap are fixed by tightening nuts *e* and *c* as required. Usually, the ends of the pipe sections are 1 to 2 cm below the rim of the end-cap when completely tight.

(9) The nuts labelled *b* are now added onto the rods to about 4 inches from the top of the rods.

(10) The top end-cap is then lowered on the rods over the pipe section, where it rests on the nuts.

(11) The nuts labelled *b* are now moved lower on the rod evenly on both sides so that the supported end-cap also moves smoothly down. Care is taken to ensure that the

end-cap is fairly level with the ground and that the air pressure release valve is open.

(12) When the end-cap does not move any further down, the nuts labelled *a* are added on.

(13) The nuts labelled *b* are now loosened while nuts *a* and *d* are tightened as required to force the pipe into the top end-cap.

(14) Both end-caps are checked for leaks and the nuts tightened appropriately in such an event.

(15) A small diameter tube is inserted into the pipe through the air pressure release valve and the pipe is filled with water to overflowing capacity, replacing air from the pipe completely.

(16) The stop valve to the pump is now connected to the pump hose and opened to flow. The pump is started with a few initial strokes, which release air trapped in the hose.

(17) The pressure release valve is kept open until all air is released and water comes from this valve with subsequent pump strokes.

(18) The pressure release valve is then closed and pumping is continued until the required water pressure of 120 psi is reached.

(19) The water pressure is maintained for two hours in the system. Then the pressure is released using the pressure release valve and the set-up dismantled in reverse order of assembly.

Many pipe sections (6 of 28 available) could not be used for the experiment since the circular ends were offset by more than 1 cm. This meant that the end-caps were not able to close the pipe ends properly, resulting in a continuos leak.

3.1.2 Testing of pipe joints

Pipe joints are designed such that they can withstand small deflections in the vertical or horizontal direction. The restraint offered by the pipe itself and the friction between the pipe and surrounding soil is often sufficient to maintain pipe connections. Efforts are made here to understand the effects of ground movements on unrestrained epoxy lined joints by causing a 2^{o} deflection in the vertical direction.

3.1.2.1 Experimental methodology

Push-on (or bell-and-spigot) pipe joints provide some flexibility without leakage, largely due to the presence of the rubber gasket in the bell part of the joint. However, the flexibility and leak-prevention of epoxy lining when used in joints is not known. A simple bending experiment was devised to determine the flexibility of epoxy lining at the pipe joints. The joint was to be deflected by 2^{o} under pressure and leakage if any, was to be noted. In order to place maximum bending stress on the pipe joint, force was applied to the flat face of the bell, while holding both ends in place. According to the simply supported beam concept, movement and stress is greatest at the centre of the span, where the joint is located in this set-up. The pipe joints were restrained to prevent longitudinal movement. Hydrostatic pressure test followed the same principles as with the straight pipe sections.

3.1.2.2 Test procedure

Four ductile-iron bell-and-spigot joints with rubber gaskets were internally coated with epoxy lining along with the pipe sections. During the lining process, the pipe joints were pushed into place tightly and wedged into a box for transportation. This was to

ensure that the joints would not move during transport from the field to the laboratory. After cure, the pipe joints were fitted with end-caps, filled completely with water and brought up to a water pressure of 120 psi. The joint was then subjected to a deflection of 2^{o} using a hydraulic jack. The water pressure was maintained at 120±5 psi for two hours. The pipe joint was closely inspected while under pressure to detect any leak or breakage in the joint area. Four pipe joints in total were tested; two of 2 mm epoxy lining thickness and the others of 1 mm thickness. The experimental set-up for pressure tests of pipe joints is shown in Figure 3.

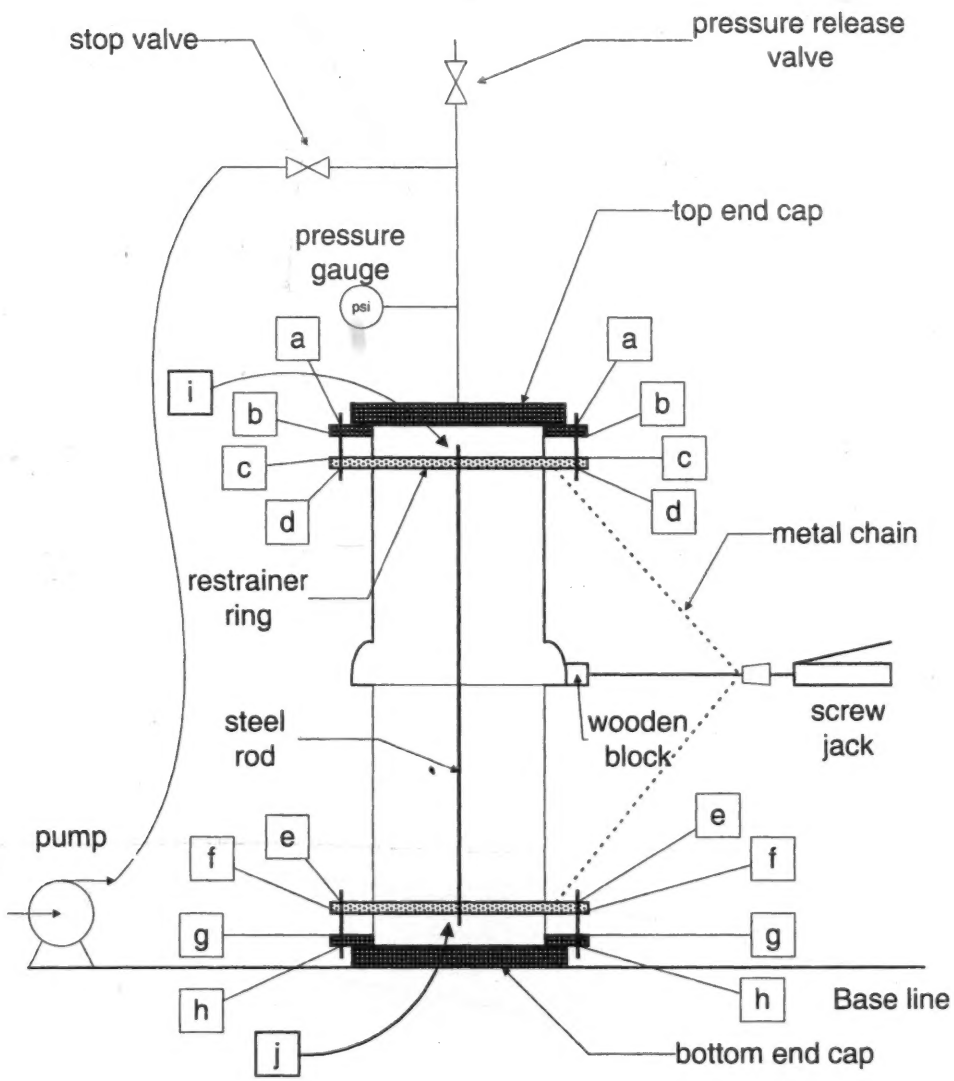


Figure 3. Experimental set-up for pressure tests of pipe joints

(1) The bottom end-cap is positioned and the seating of the rubber O-ring (not visible in Figure 3) inside the end-cap is checked.

(2) The joint section is removed from the transportation box, taking care not to disturb the joint.

(3) The restraining rings are slid onto the top and bottom parts, leaving 6 in. from the ends.

(4) The restraining rings are then tightened to the pipe while keeping the rings perpendicular to the pipe axis.

(5) A metal chain is slipped around one restraining ring and the mechanical hoist is used to lift the section above ground.

(6) The joint section is positioned vertically so that the holes in the restraining ring and the bottom end-cap are aligned.

(7) Two short steel rods are passed through the aligned holes on either side of the pipe joint. The rods will be diametrically opposite to each other.

(8) In the order of *f*, *g*, *e* and *h*, the nuts labelled thus are put on and the pipe is forced into the end-cap using the nuts that are labelled *e* and *h*.

(9) Two long steel rods are passed through the two restraining rings on either side, to keep the joint from moving apart longitudinally while under pressure.

(10) The nuts labelled *i* and *j* are used to tighten the rods in place.

(11) The set-up is then filled with water to check for leaks in the bottom end-cap and the joint.

(12) The top end-cap is put on such that the holes in it are aligned with those of the restrainer ring closest to the top.

(13) Two short steel rods are passed at diametrically opposite ends through the aligned holes at the top.

(14) The nuts are now put on in the order of *b*, *c*, *a* and *d*, while the pipe is forced into the end-cap using nuts labelled *a* and *d*.

(15) Water is filled to overflowing and all air is released from the system using the pressure release valve.

(16) The pump is connected to the stop valve, which is then opened. The water pressure is brought up to 120 psi by pumping.

(17) The pumping is stopped and a metal chain is slipped through both restraining rings.

(18) A rounded block of wood is placed at the joint as shown in Figure 3 and the chain is hooked onto the screw jack.

(19) The chain is jacked up using the pumping arm of the screw jack until the chain is taut.

(20) The distance moved by the tip of the jack from the wooden block while tightening the chain is measured. Pumping is resumed to bring up the water pressure to 120 psi.

(21) The jack tip is further pushed to a distance of 1.1 cm to achieve a 2^{o} angle of deflection.

(22) The jack is held in place by tension and water pressure is maintained at 120 psi for 2 hours.

The steel washers were used with the nuts to restrict their movement on the rods and to provide a tight fit.

3.2 Field leaching tests

In the field, the cast iron water mains were lined with Nitoline WP® epoxy resin following the standard procedure outlined in the publication "In Situ Epoxy Resin Lining – Operational Guidelines and Code of Practice" published by the Water Research Centre, U.K (Seargeant, 2001). After the epoxy coating was air-cured, the mains were disinfected with super-chlorinated water at a chlorine concentration of about 50 mg/L.

3.2.1 Super-chlorinated water samples

The hydrant valves were opened after the disinfection and the super-chlorinated water was allowed to discharge for a minute and then collected in prepared bottles. An amber bottle of 1L capacity was used to contain the samples to test for turbidity and UV_{254} absorbance. Samples for VOCs were collected in 40-mL gas chromatography (GC) vials that contained ascorbic acid as dechlorinating agent. The super-chlorinated water samples were tested for turbidity, UV_{254} absorbance and volatile organic compounds.

3.2.2 Domestic drinking water samples

Flushing of the mains was then continued with potable water and samples were collected and tested for bacterial counts. The bacteriological test results for fecal coliform was less than 1 cfu (colony forming units) per 100 mL, which indicated that the colony counts were negligible. The next day, these mains that were disconnected from the rest of the drinking water network for epoxy lining, were put back into service. Water samples were obtained from customers' homes that were fed from the freshly epoxy-lined mains as soon as the mains were in service. These grab samples were taken weekly up to a month after restoration of service. The water samples obtained directly from the

customers' taps were tested for turbidity, UV_{254} absorbance, volatile organic compounds (VOCs), total residual chlorine and flavour profile analysis (odour test). The sampling regimen was as described in Table 3.

Table 3. Sampling regimen for field samples

Description	Sampling Date	
	Phase 1	Phase 2
Background samples from selected houses	-	17 Sep 2001
Super-chlorinated samples from hydrants	8 Aug 2001	15 Oct 2001
Flushed potable water from hydrants	17 Aug 2001	18 Oct 2001
First day in service, from houses	17 Aug 2001	18 Oct 2001
Third day in service	20 Aug 2001	-
Tenth day (1 week) in service	27 Aug 2001	24 Oct 2001
1 month in service	17 Sep 2001	16 Nov 2001

3.2.3 Experimental procedure

The sampling procedure for domestic samples involved opening the cold-water tap in the customer's kitchen and letting the water flow at a moderate rate for 3 minutes. The kitchen tap was selected in all cases, as it was the most likely source of drinking water for the household. Houses that had water softeners or filters were excluded from this study. As in the case of the super-chlorinated samples from hydrants, a 1L amber bottle was used for samples to test turbidity, total residual chlorine and UV_{254} absorbance. Another 1L amber bottle was filled with water to test for odour. Samples for chromatographic analysis were collected in 40-mL GC bottles. The super-chlorinated samples and those of the first day of resumed service, were also sent to the Alberta Research Council (ARC) to test for semi-volatile compounds. These samples were collected in special 1L amber-coloured bottles that were provided by ARC. All water samples were transported in

coolers containing ice packs to the EPCOR Water Quality Assurance Laboratory as soon as sampling was completed.

Five primary water quality tests were conducted to analyse samples obtained from the field. These were tests for turbidity, odour, total residual chlorine, UV_{254} absorbance and volatile organic compounds, conducted using the EPCOR Water Quality Assurance Laboratory facilities. Alberta Research Council (ARC) carried out the analysis for semi-volatile compounds. All test methods followed the procedures outlined in the Standard Methods in the Examination of Water and Wastewater Methods (APHA et al., 1998).

Turbidity: Turbidity is a measure of the clarity of water since it indicates the presence of any suspended or colloidal matter. Turbidity was determined using a HACH 2100 N Turbidimeter and the nephelometric method of turbidity measurement was followed, as given in the section 2130 B of Standard Methods for the Examination of Water and Wastewater (APHA et al., 1998). After the instrument was calibrated, the sample in the cell was degassed by placing it in an ultrasonic bath for a few seconds. The cell was inserted into the sample compartment of the instrument and the reading was allowed to stabilise before it was recorded. The units of turbidity are given as Nephelometric Turbidity Units or NTU.

Flavour profile analysis (Odour test): Odour tests are important in determining the acceptability of drinking water to the consumer. Apart from aesthetic considerations, the human nose is quite sensitive in detecting trace contaminants that may be present in

quantities below instrumental method detection limits (MDL). A panel of trained personnel, which included some of the authors of this work, followed the method given in section 2170 B of Standard Methods for the Examination of Water and Wastewater (APHA et al., 1998) to evaluate the water samples. The sample flask was kept in a water bath for 15 minutes at 25 °C, after which it was taken out, swirled and the flask opening was sniffed. The odour was rated on a 0 to 3 scale with the following representations:

0 no odour detected

0.25 trace (unidentifiable odour)

0.5 slight identifiable odour

1.0 slightly objectionable odour

2.0 moderately objectionable odour

3.0 objectionable odour (not drinkable)

Total residual chlorine: For optimal water quality, a desired residual chlorine concentration is maintained in the water flowing through the distribution system. This residual is comprised of free chlorine and combined chlorine (monochloramine and dichloramine), together called total residual chlorine. It was measured using a Wallace and Tiernan Amperometric Titrator, which used 0.00564 N phenyl arsine oxide as the titrant. Total residual chlorine was determined amperometrically at pH 4 in the presence of potassium iodide. The units of total residual chlorine are given as mg/L.

UV_{254} absorbance: The UV_{254} absorbance of a water sample is a measure of semi-volatile and non-volatile organic compounds present in water. The absorbance was

determined using a UV 2101 PC Spectrophotometer that was set to a wavelength of 254 nm. The sample was dechlorinated using sodium thiosulphate, filtered and placed into the spectrophotometer slot to obtain the reading. The reading was multiplied by 25 when using a 4 cm sample cell to obtain a value in Abs/m.

Volatile organic compounds: The amounts of volatile organic compounds, especially trihalomethanes, in drinking water are regulated by health authorities in the US and Canada. About 24 compounds in this category were screened using gas chromatography. The instruments used were Varian 3400 GC/FID and Tekmar 3000 purge and trap GC with Tekmar Precept II autosampler. The automatic sampler uses a 40 mL vial specified for water analysis that has a teflon-lined silicone septum. Vials are loaded into a rack and sequentially led to a sampling station. Sample collected by piercing the septum is directed through a filter, a sampling loop, and then injected into the purge vessel on the purge and trap unit. An internal standard is automatically added. Accuracy and precision of the instruments were checked using a 200 µg/mL toluene standard obtained from Sigma-Aldrich Canada. The instruments proved to be 95% accurate and duplicate runs were within 4% of each other.

3.3 Laboratory leaching tests

3.3.1 Experimental methodology

Prior to this study, the EPCOR Water Quality Assurance Laboratory had conducted a regimen of leachate studies to determine if any chemicals were migrating from the lining material into the drinking water. The results of GC/MS analysis indicated the presence of no harmful chemicals in the laboratory samples. It was decided that field samples would also be studied to confirm this conclusion. Also, independent testing of the material by leaching with water was to be carried out at the Environmental Engineering Laboratory at the University of Alberta to test for harmful leachate. To this effect, clear glass bottles were lined with the Nitoline® epoxy lining material and subjected to leaching with water. The effects of three important factors upon leaching - temperature, thickness of lining material and type of water used for leaching - were studied.

3.3.2 Volatile and semi-volatile organic compounds

Twenty clear glass bottles of 4 L capacity were manually spray-lined with epoxy resin on the inside and allowed to cure at the temperatures specified in Table 4. Two blanks for tap water and Milli-Q water were maintained as control for the experiment. A total of 16 epoxy-coated bottles were used in the experiment, half of which were cured at 4 °C and the other half at 20 °C. These temperatures were chosen to represent the range of water temperature in the distribution system. The thickness of 2 mm was obtained by spraying the bottles twice, as in the case of pipe samples in the pressure tests. The bottles were thus cured and maintained at 4 °C and 20 °C respectively. After curing, 8 bottles were filled to overflowing with de-ionized water purified by a Milli-Q system and the

other 8 with tap water. The experimental design was a 2^3 full factorial design with the conditions as follows in Table 4.

Table 4. Conditions set in factorial experimental design for laboratory leaching test

Factors	Low	High
Temperature of cure	4 °C	20 °C
Thickness of lining	1 mm	2 mm
Type of water	Milli-Q	Tap water

Teflon-lined lids were used to close the bottles and zero headspace was maintained. The size of bottle was chosen to closely emulate a 6 in. diameter sealed pipe section. Magnetic stirrers were used to create laminar shear by water on the bottle walls. The surface area of the bottles in contact with water was approximately 957 cm^2 for each bottle. Samples were drawn from the bottles regularly up to a month and were analyzed on a GC at the EPCOR Water Quality Assurance Laboratory. After sampling, the zero headspace was maintained by topping up with tap water or Milli-Q water as required. Some samples were also tested for the presence of semi-volatile compounds classified as "extractable priority pollutants" and these tests were conducted by the Alberta Research Council.

3.4 Water absorption tests

3.4.1 Experimental methodology

It is well known that above the glass transition temperature (T_g) of a paint film, the resin molecules are more active and hence change the physical properties such as hardness, water permeability, plasticity, etc (Suzuki, 1989). It has also been reported that the water content of a film lowers its T_g value by about 30°C. The manufacturers of the presented epoxy lining have established the T_g of the cured epoxy film to be 47°C, which is considered low for an epoxy resin (Ellyin, 2001) (usual T_g value for epoxy resins is about 80°C (Suzuki, 1989)). Two temperatures were assigned to allow for accelerated testing studies: room temperature (approximately 27°C) and high temperature (40°C). It was determined that 40°C was the highest temperature that would be sufficiently below the T_g of 47°C while also providing data for accelerated testing. However, it was noted that if the T_g of the resin did reduce by 30°C (to 17°C) due to the water absorption, both laboratory temperatures would be above this modified T_g of 17°C.

3.4.2 Test Procedure

The water absorption test procedure followed the ASTM Standard D570–98 (ASTM, 1998). The cured epoxy lining material was cut into 4 sections of dimensions approximately 4.5x3.5 cm, held at one end and immersed in water. Two continuously mixed water tanks were used for this test, one maintained at room temperature and the other at 40°C. The initial weights of the specimens were recorded. Post immersion, the weight of the specimens was measured at 10^0 (or 1) hours, 10^1 (or 10) hours, 10^2 (or 100) hours and thereafter every 7 days (or 168 hours). At the specified time, the specimens were removed from the tanks, wiped dry with paper towels and a stable weight reading

was recorded within the first 5 minutes. Weekly measurements were stopped after 3 months, but the specimens were allowed to remain in the mixing tanks for up to 9 months. Specimens were weighed again at the end of this period to record a final weight.

4. Results and Discussions

4.1 Pressure tests

4.1.1 Pressure tests with pipe sections

A visual examination of the lined pipe sections prior to testing indicated that in most cases the lining formed a good bond with the pipe and provided a smooth finish on the inside surface. Fourteen of the 24 lined pipe sections were selected for testing, while 4 were rejected due to minor cracks in the lining and some detachment of lining from the pipe. The detachment occurred since the lining adhered to loose rust particles without bonding to the pipe. This shows the importance of proper cleaning of the internal surface of the pipe prior to lining. Six pipe sections were rejected since the pipe sections were cut unevenly, causing leaks at the end caps before the start of the experiment. In some pipe sections it was observed that the exposed circular lining areas were not flat but had slight elevations, caused by the pressure of the spray against the soft putty in the lining process. This was, however, considered a minor issue and these pipe sections were included in the experiments. During the lining process, the pipe sections were laid with the holes facing upwards so that the slumping of uncured epoxy lining material, if any, would not increase the thickness at that part. The pipe sections were kept at 120 psi by pumping water continuously. However, it was found that the system stabilised after about an hour and the leakage observed at the end-caps in all pipe sections was reduced. Leakage was not measured, as it did not serve the objective of the test. The results of the hydrostatic pressure test are summarized in Table 5. Hydrostatic pressure values in Table 5 indicate the final hydrostatic pressure reached by the individual pipe sections before rupture. The % success refers to the number of replicates that were able to withstand the applied 120

psi pressure for 2 hours. For example, if 2 out of 3 replicate pipe sections ruptured, the % success is 33% (1 out of 3).

Table 5. Results of pressure testing of pipe sections

Sample no.	*Lining thickness (mm)*	*Diameter of exposed lining (in)*	*Hydrostatic pressure (psi)*	*Time under pressure (hr)*	*Rupture location*	*% success*
1	1	0.75	105	0	top	0
2	1	0.75	45	0	top	
3	1	0.5	5	0	middle	33
4	1	0.5	120	0	top	
5	1	0.5	120	2		
6	1	0.25	5	0	top	67
7	1	0.25	120	2		
8	1	0.25	120	2		
9	2	0.75	120	2		100
10	2	0.75	120	2		
11	2	0.5	120	2		100
12	2	0.5	120	2		
13	2	0.25	120	2		100
14	2	0.25	120	2		

From Table 5 it is seen that the increased thickness of lining generally increases its rupture resistance or strength. It is also seen that the exposed lining material in some pipe sections ruptured even before the maximum pressure of 120 psi was achieved. Triplicates were used for 1 mm thick lining exposed in ½ in. and ¼ in. diameter, since one specimen burst at 5 psi and the other at 120 psi. During the experiments it was observed that any imperfections in the 1 mm lining reduced its strength drastically. This was indicated by the break pressure of the lining, which ranged from 5 psi to 120 psi regardless of the size of holes covered. Among the lining rupture locations on the pipe section, all except one ruptured at the top location, while one ruptured at the middle. The pressure surge with each stroke of the pump may have affected the top location before it dissipated to lower

parts of the system. The lining is considered to be of similar thickness at all three locations since the pipes were lying horizontal while being lined.

From the data in Table 5, it was seen that the increased thickness of lining seemed to increase its rupture resistance or strength. This effect of thickness on lining strength was confirmed by a subsequent regression analysis of the data and is detailed in Table 6. In this case, the rupture resistance depended on three predictors – break pressure, thickness of lining and diameter of exposed lining area. These three factors were put into the multiple regression and the output values were denoted as 0 for lining rupture and 1 for successful resistance. The analysis of variance (ANOVA) generated from this regression provides more information about the relative significance of each factor.

Table 6. Results of pressure test data regression

Regression	*Statistics*
Multiple R	0.854
R Square	0.729
Adjusted R Square	0.647
Standard Error	0.295
Observations	14

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	2.34	0.781	8.96	0.0035
Residual	10	0.871	0.087		
Total	13	3.21			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.188	0.310	-0.606	0.558	-0.88	0.504
Pressure	0.00602	0.00211	2.85	0.0174	0.0013	0.0107
Thickness	0.406	0.181	2.24	0.0489	0.0022	0.809
Diameter	-0.692	0.397	-1.74	0.112	-1.57	0.192

The R square value of 0.729, which is close to 1, and the significance F value being much smaller than the F value, both indicate a significant regression. Thus it is evident that the input factors do significantly influence the rupture resistance of the lining. The lower and upper 95% confidence intervals for pressure and thickness do not include zero, which indicates that within this experimental range, these factors are highly significant when compared to the diameter factor. The pressure and thickness factors both have a positive effect on the outcome of successful rupture resistance, as shown by the positive value of their coefficients. Thickness has a greater effect than pressure since it has a higher coefficient, thus confirming that thickness is the most important factor affecting rupture resistance or strength of the lining. In this case the coefficients are not used to build a model since it would have limited predictive power beyond the tested experimental range. It is not known whether the lining would exhibit similar behaviour under sustained pressure for a longer period of time. For further testing, it is recommended that the pressure be maintained for a longer period of time as in tests involving structural liners.

It was observed that if the lining material did not rupture within the first 10 minutes, it would handle the test pressure throughout the remaining test period. This observation is consistent with the report that collapse during short-term tests occurs typically within one hour (Bakeer et al., 1999). An issue associated with the strength of polymer lining is the phenomenon of creep. This viscoelastic property of a polymer material describes its loss of strength with time and is exhibited at most temperatures of product use. Further research is definitely warranted in this area to make service life predictions. The most important observation of this experiment is the highly reliable

performance of the lining at 2 mm thickness. The second epoxy-lining layer bonded seamlessly with the first layer to produce the double thickness. It appears that the next layer resolves the unevenness of the first 1 mm layer caused by irregularity in the underlying pipe. It can be safely assumed that the lining at this thickness would protect corroded pipes from disintegration in normal conditions. Since the pressure of 120 psi is used to test the installation of water mains, this observation can be related to epoxy-lined pipes carrying water underground. These pressure tests can be regarded as an industrial-scale test to evaluate the application and performance of lining materials having similar product specifications.

From this set of tests, it is evident that 2 mm (80 mils) thickness of lining material is preferable over the standard 1 mm (40 mils) thickness, which is the minimum requirement recommended by the manufacturer, FOSROC International Limited, to provide uniform holiday-free coverage for corrosion protection. At 1 mm thickness, the epoxy lining would still reduce the red water problems. The National Sanitary Foundation, U.S., requires that the maximum field use dry-film thickness per coat should be 1 mm (40 mils) for the use of epoxy as barrier material. Therefore the 2 mm thickness of lining was obtained by spraying twice rather than once at double thickness. The difference between applying a single 2 mm thick lining and two consecutive 1 mm linings was not examined, therefore it is not known if the results would differ for the single spray mode. The cost of additional material used in lining may be offset by the increased reliability of lined pipes. The cost of spray lining is approximately CAD $125 per metre, while that of a single spray coat is CAD $25 per metre (Seargeant, 2001). Applying the second coat after the 16 hour cure time would therefore increase the cost by

CAD $25 per metre, not including other working costs. However, care must be taken to ensure the thickness is not beyond 2 mm nominal thickness. Slumping is a potential problem with applying the epoxy resin too thickly. Early cracking, blistering and loss of adhesion may also occur with the application of too much thickness.

4.1.2 Pressure tests with pipe joints

It was observed that due to the brittle nature of the cured epoxy resin, the lining material was not able to withstand any bending at the joints. In fact, it even failed to bridge over the inner surface of the push-on joint. Since the spigot fits into the bell, the inner surface of the spigot was closer to the axis of the pipe than the inner surface of the bell. Thus the epoxy lining spray encountered a sharp surface drop-off at the joint. Since this was a new pipe, no underlying material would be deposited to form a smoother surface. A visual examination of the inside surface showed the lack of 100% coverage of the epoxy resin at the joints. It is expected that this may not be the case in a used pipe, as it would have enough carbuncles and scale residue to provide an even surface for the spray.

Table 7. Results of the pressure test with joints

Thickness of lining (mm)	Angle of deflection (degrees)	Water pressure (psi)	Distance moved at centre (cm)
1	2.7	120	1.1
2	2.3	120	1.1
1	2.6	120	1.1
2	2.9	120	1.1

The joints withstood the 2^{o} deflection for 2 hours under pressure even though the epoxy lining had failed. Epoxy lining failure, as indicated by the ruptured epoxy lining at

the joint, was observed in all the pipe joints when the water was drained out of the experimental set-up. As seen in Table 7, the average angle of deflection at the joint was 2.6° rather than 2° as measured. The difference in deflection angles was due to the difference in length of the joint sections. At the end of tests, one joint was allowed to bend up to 11°. It showed no leaks from the joint since the gasket provided excellent seal. Longitudinal movement of the pipe joint is possible under pressure, which was eliminated by long steel rods placed across the pipe joint during all experiments.

According to R.W. Bonds, the maximum deflection (y_r) allowable at mid-span of a pipe to prevent damage to the internal cement-mortar lining is given by

$$y_r = L/10 \qquad \text{Equation 4}$$

where L is length of the span (ft) and y_r is the maximum allowable deflection at mid-span (inches) (Bonds, 1990). This equation can be adapted to the present study of internal epoxy lining, which calculates y_r to be 0.4 in. or 1.02 cm for the span of 4 ft. in the experimental pipe joints. The deflection used in the experiments was 1.1 cm to obtain a deflection of 2° at the centre of the span, which is 8 % more than what is allowable for the span. Thus we can conclude that the epoxy lining will not sustain a deflection of 2° at the joint sections and is not more flexible than cement-mortar lining for this purpose. Therefore, special care must be given to the application of spray lining at joints, since inadequate coverage was found at the internal bell-spigot junctions.

4.2 Field leaching tests

A total of 76 chemicals were screened in the 41 samples obtained during field tests, which includes the samples from hydrants. Of these, 53 compounds were semi-volatile organic compounds classified as extractable priority pollutants by the Alberta Research Council (ARC), Canada. Gas chromatography was used to identify the 23 volatile organic compounds, especially trihalomethanes whose amounts in drinking water are regulated. Table 8 provides the maximum concentrations of the tested compounds recorded during the entire testing regimen and compares it with existing regulations in Canada (Health Canada, 2002) and the US (US Environmental Protection Agency, 2002).

Some of the semi-volatile compounds in Table 8, such as diethyl phthalate and di-n-butyl phthalate, are not currently regulated in drinking water by Health Canada. Hence, no guidelines were available for comparison of these compounds. Polycyclic aromatic hydrocarbons such as benzo(a)antracene are also not regulated under the guidelines. The maximum contaminant level (MCL) values given for the compounds are enforceable standards that must be met by all operating water utilities in the US. The US Environmental Protection Agency has stated that some chemicals in drinking water are currently being monitored under its Unregulated Contaminant Monitoring Regulation (US Environmental Protection Agency, 2002). Industry sources, however, indicate that some of these semi-volatile compounds are likely to be regulated by health authorities in the near future.

Table 8. Results of chemical tests with epoxy-lined bottles and field tests

Chemical name	*Canadian Drinking Water Guidelines*		*USEPA Drinking Water Standards*	*Maximum concentrations obtained*		
	MAC	*AO*	*MCL*	*Bench tests*	*Field tests*	
					House	*Super-chlorinated*
Semi-volatile compounds analysed at ARC (in ppb)						
Di-n-butyl phthalate	n/a	n/a	n/a	**0.3**	**1.0**	**1.5**
Phenanthrene	n/a	n/a	n/a	0.0	**0.2**	0.0
Pyrene	n/a	n/a	n/a	0.0	0.0	**0.8**
2,4,6-trichlorophenol	5	≤ 2	✓	0.0	**1.9**	0.0
Benzo(a)anthracene	n/a	n/a	n/a	0.0	0.0	**0.3**
Benzo(b)fluoranthene	n/a	n/a	n/a	0.0	0.0	**0.2**
Bis(2-ethylhexyl)phthalate	n/a	n/a	n/a	0.0	**0.1**	**1.8**
Chrysene	n/a	n/a	n/a	0.0	0.0	**0.4**
Diethyl phthalate	n/a	n/a	n/a	0.0	0.0	**0.2**
Fluoranthene	n/a	n/a	n/a	0.0	**0.2**	**0.9**
Volatile organic compounds analysed at EPCOR Water Laboratory (in ppb)						
Chloroform	*	n/a	n/a	**24.5**	**23.1**	**10**
Dichloromethane	50	n/a	5	**0.7**	<0.5	<0.5
Bromodichloromethane	*	n/a	n/a	**1.2**	**1.3**	**0.6**
Toluene	n/a	≤ 24	1000	**267.4**	**0.6**	< 0.5
Total xylenes	n/a	≤ 300	10,000	**2.6**	< 1.0	< 1.0
Water quality parameters tested at EPCOR Water Laboratory						
Total residual chlorine (mg/L)	3	n/a	< 4	n/d	**1.97**	**70.0**
Turbidity (NTU)	1	≤ 5	< 1	n/d	**0.62**	**30.7**
UV_{254} absorbance (Abs/m)	n/a	n/a	n/a	n/d	**2.3**	**18.5**
Odour intensity (no units)	n/a	in-offensive	n/a	n/d	**1.0**	n/d

MAC Maximum Acceptable Concentration (Canada)
AO Aesthetic Objective (Canada)
MCL Maximum Contaminant Level (US)
n/a not available
n/d not determined
< x less than Method Detection Limit
* belongs to class of trihalomethanes, total MAC = 100 ppb
✓ monitored under Unregulated Contaminant Monitoring Regulation (USA)

The objective of these tests was to determine if the epoxy lining released any trace compounds of concern into drinking water. Since water samples were obtained from hydrants after superchlorination and drinking water supplied to the public, these will be discussed separately in the following paragraphs.

A few super-chlorinated water samples obtained from the hydrants indicated traces of semi-volatile compounds as seen in Table 8. This super-chlorinated water was used for disinfecting water mains and was flushed out as per operational procedure. The average value of turbidity for the super-chlorinated samples was found to be 10.5 NTU, while the average UV_{254} absorbance was 23.9 Abs/m. High turbidity was observed in the hydrant samples, but not in the drinking water samples from customers' taps. The procedure of flushing is known to disturb sediments in the distribution system, both in the hydrants and in the surrounding pipe network. The super-chlorinated water is used to disinfect the mains and is not delivered to customers. Lower amounts of volatile compounds were found in super-chlorinated samples when compared with drinking water samples. This may be due to the volatilisation of these chemicals while sampling from the gushing hydrants.

Drinking water samples obtained on the first day in service did not contain any chemicals above established aesthetic limits as indicated in Table 8. The drinking water samples met regulatory requirements and average values obtained were 0.45 NTU turbidity, 1.76 Abs/m UV_{254} absorbance, odour intensity of 0.58 and 1.6 mg/L total residual chlorine for the entire period of field tests. These values fall within normal ranges seen in the drinking water. Similar values were obtained from the house connected to an unlined part of the distribution system. The odour descriptions ranged from sweet,

musty and sour to chlorine and solvent-like smells. Consistently low values (on a five-point scale) were given to all odour samples. The sample obtained after a month in service was tested at ARC, which showed no unusual peaks or compounds, ruling out the possibility of leaching of the resin constituents during this time period.

By all the standard tests described in the Materials and Methods Section, the water was of excellent quality. Following the lining program, no red water complaints were received by the utility. Based on the tests detailed above, the epoxy lining is verified as being safe for contact with drinking water. For further tests, a more corrosive environment may be used, since it may better simulate the actual conditions of ageing and deterioration of the lining material. Toluene was found in the lined bottles but not in the drinking water from the field, which is discussed in the following section on laboratory-scale leaching tests.

4.3 Laboratory leaching test results

Of the volatile compounds listed in Table 8, toluene only was identified as not present originally in the contact water added to the bottles. Thus only one of the 23 volatile compounds tested had leached solely from the lining. This was in accordance with the findings of the earlier static leaching tests. Laboratory tests also revealed that Milli-Q water showed no aggressive leaching tendencies, while tap water leached no additional chemicals. The test was conducted in duplicate and the average of the duplicates was used for analysis. Usual quality assurance/ quality control guidelines of the EPCOR Water Quality Assurance Laboratory were practised during both sampling and testing steps. The trend of toluene leaching obtained is depicted in Figure 4.

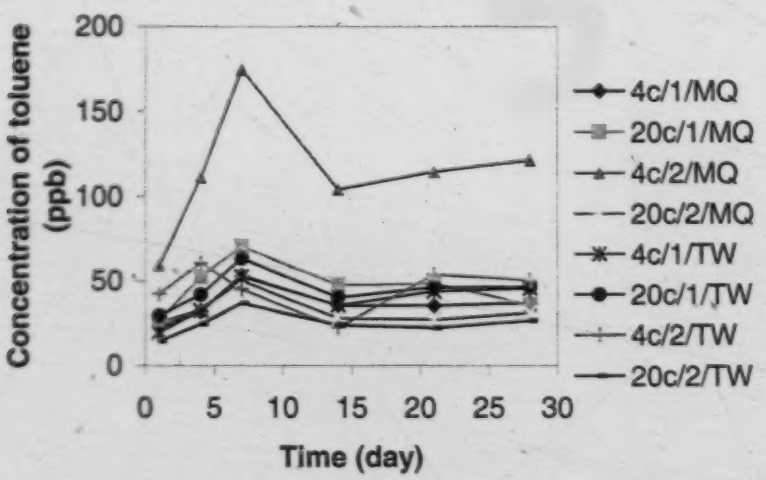


Figure 4. Average leaching of toluene from bottles in one month

The legends of Figure 4 are in the format of temperature(°C)/thickness(mm)/water type. For example, 4c/1/MQ means the duplicate bottles maintained at 4 °C, each with 1 mm thick epoxy lining and containing Milli-Q water. The range of toluene concentration in the bottles was 14.2 to 59.1 ppb on the first day, which increased slightly in the range

of 12.3 to 63.1 on the seventh day. The toluene concentration in leachate did not seem to increase substantially even with 28 days of contact. This indicates that all the toluene measured was leaching only from the surface and not diffusing through the thickness of the lining material. As seen in Figure 4, one of the bottles under the conditions 4c/2/MQ as shown by the high curve, exhibited an exceptionally high level of toluene in the contact water. The duplicate bottle that was maintained at the same conditions did not show this high value. This difference between duplicates is highlighted in Figures 5 and 6. In Figure 5, the first duplicate under the conditions 4c/2/MQ (values indicated by triangular points) exhibits the maximum amount of toluene leaching. In Figure 6, the duplicate at the very same conditions exhibits a much lower toluene leaching.

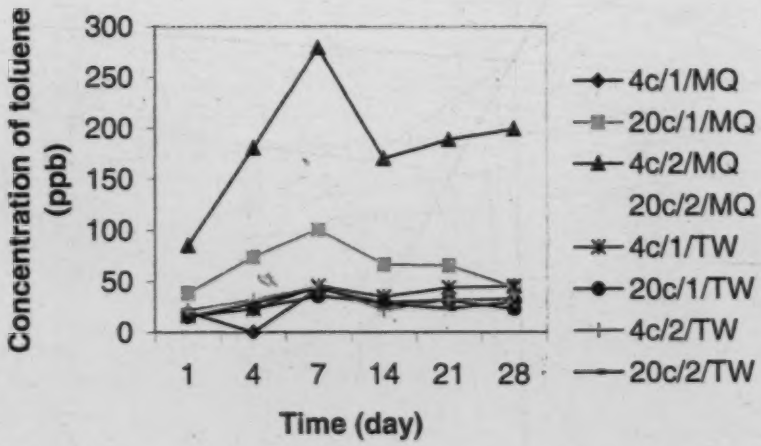


Figure 5: Trend of toluene leaching in duplicate 1

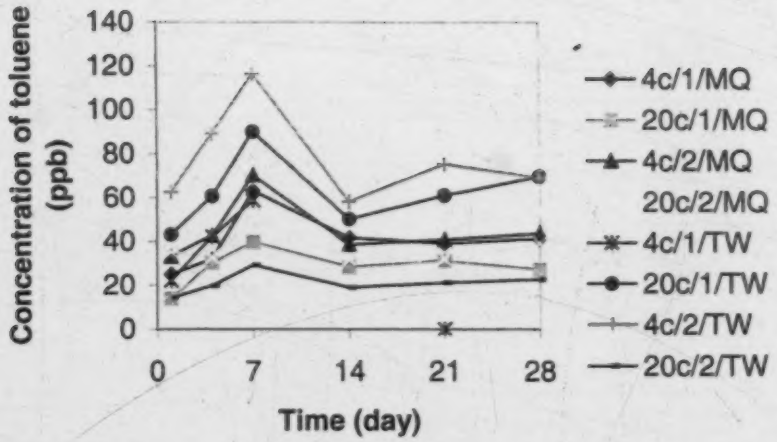


Figure 6: Trend of toluene leaching in duplicate 2

To understand this variation, a separate time-ordered test was conducted to link toluene concentration with the order in which the bottles were lined. Another 16 bottles were cured and maintained at similar conditions as before. Results of this later test showed that the first bottle lined had a very high toluene concentration and the toluene dropped exponentially in the successive bottles, as seen in Figure 7. Thus the bottles maintained at the same conditions cannot be said to be true duplicates of each other, since they started with variable concentrations of toluene in the lining.

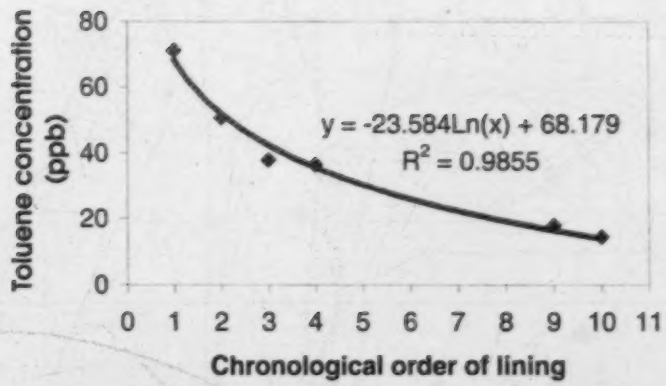


Figure 7. Trend of toluene concentration with order of lining

The source of toluene found in the laboratory samples was traced back to its use in cleaning the spray-head of the lining rig. The cleaning liquid was previously identified only as FOSROC Solvent 102 in the product description. The epoxy lining applicators in the field confirmed that the solvent was in fact toluene. Continuous spraying would purge the toluene from the spray head causing the exponential decrease of toluene seen in successive bottles. The concentration of toluene was reported as either zero mg/L or less than MDL for all field samples of drinking water, as shown in Table 8. This is definitely due to the post-cure flushing operation that is standard practice in spray lining. When the lined bottles were rinsed out and refilled to correlate the laboratory bottle testing data with the field samples, the expected concentration drop to near zero was obtained. Water in the distribution system pipes is continually renewed from other sections, unlike the laboratory bottle testing test set-up. Toluene is not expected to be a problem in real life

scenarios, because any toluene contamination from the spray head during lining would be flushed out with the super-chlorinated water during the initial flushing.

According to the toluene health advisory released by the US Environment Protection Agency, a maximum concentration of 1 mg/L of toluene in drinking water is not expected to cause any adverse non-carcinogenic effects for a lifetime of exposure (USEPA, 2002). This value is based on a 70-kg adult consuming 2 L of water per day. Moreover, toluene is not classified as a carcinogen in their list.

The factorial design of the experiments was based on the assumption that some volatile chemicals would leach from the lining and the effects of the experimental conditions on this leaching would be studied. However, none of the tested chemicals leached from the lining itself. Toluene, which was selected as the indicator compound based on earlier static tests, was established to be a contaminant that is not an integral part of the epoxy lining. The toluene concentration in the bottles was not greatly influenced by the subsequent conditions of cure. The trend of leaching for most of the combinations of conditions followed the same pattern, as seen in Figure 8 and Figure 9 below. The tap water and Milli-Q water samples are represented on separate figures for ease of illustration.

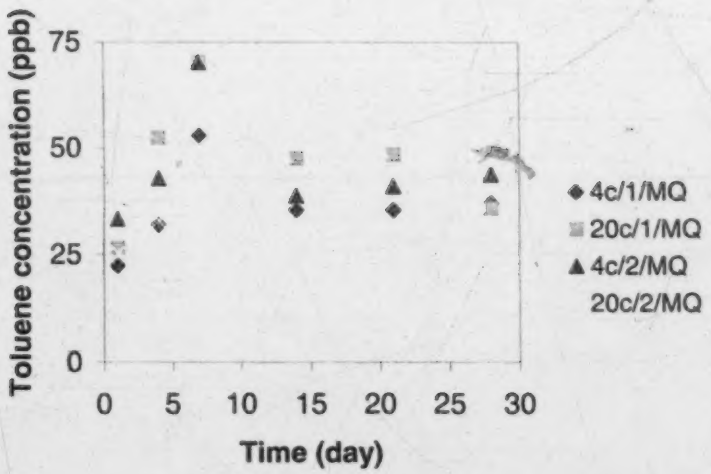


Figure 8. Average toluene leaching for one month in Milli-Q water

Here we find that there is no perceptible difference between the behaviour of samples maintained at 4 °C versus 20 °C, and 1mm lining thickness versus 2 mm. For example, let us assume that 2 mm thickness must contain more toluene than 1 mm. Therefore, the curves corresponding to 4c/1mm/MQ and 20c/1mm/MQ should always be lower than their corresponding 2mm counterparts. This is, however, not the case with the 20 °C samples. Next, let us assume that the 4 °C condition releases more toluene than 20 °C due to improper epoxy curing. Therefore, the curves corresponding to 4c/1mm/MQ and 4c/2mm/MQ should always be higher than their 20 °C counterparts. Again, this is not the case with the 4 °C samples. On the other hand, the higher temperature of 20 °C may be assumed to consistently leach more toluene, which is also not the case. Thus it can be concluded that temperature and thickness do not cause significant variation in either the leaching trend or concentration of leachate. This behaviour is also exhibited by the tap water samples as shown in Figure 9.

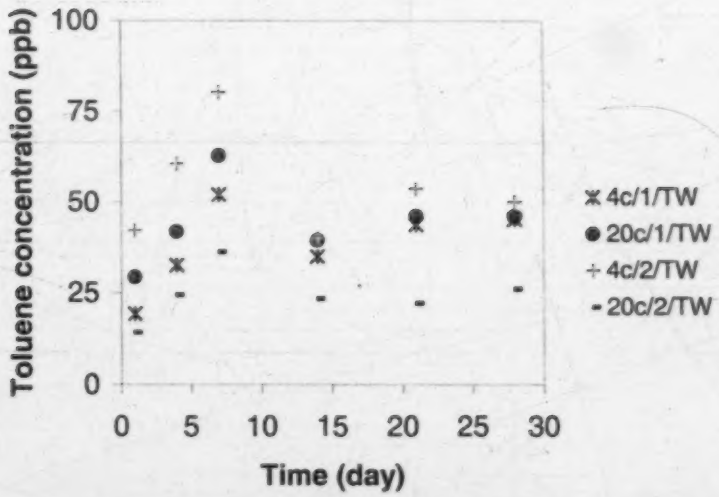


Figure 9. Average toluene leaching for one month in tap water

From the leaching tests, the following conclusions may be drawn. First, the temperature during cure did not seem to affect leaching. This implies that the epoxy lining material performs well even under low temperatures. Second, the double lining thickness of 2 mm did not affect leaching. Thus the recommendation from the pressure tests to use a 2 mm lining thickness is supported. Also, the normal constituents of tap water did not leach any additional chemicals from the lining. Thus, it may be expected that the lining is non-reactive with normal tap water. Milli-Q water did not show aggressive leaching tendencies either. The leaching of toluene appears to be largely a surface phenomenon, since the concentration of toluene remained nearly constant after the initial peak. Since no other chemicals of concern were found during the initial GC/MS and subsequent analyses, it may be concluded that the epoxy lining serves the purpose of internal corrosion protection while complying with drinking water regulations.

The findings of the trend of toluene leaching from this study are in good agreement with an early study on epoxy resins. Alben (1989) reported an exponential decrease in leached chemical concentration from epoxy resin with time (Alben et al., 1989). A similar trend was found in this study for the laboratory samples leached with tap water and Milli-Q water, as shown in Figure 10 and Figure 11. The figures illustrate the exponential trend, with average R^2 values of 0.83 and 0.82 respectively, suggesting a good fit with the data. The y-axis represents the change in toluene concentration with time (dc/dt).

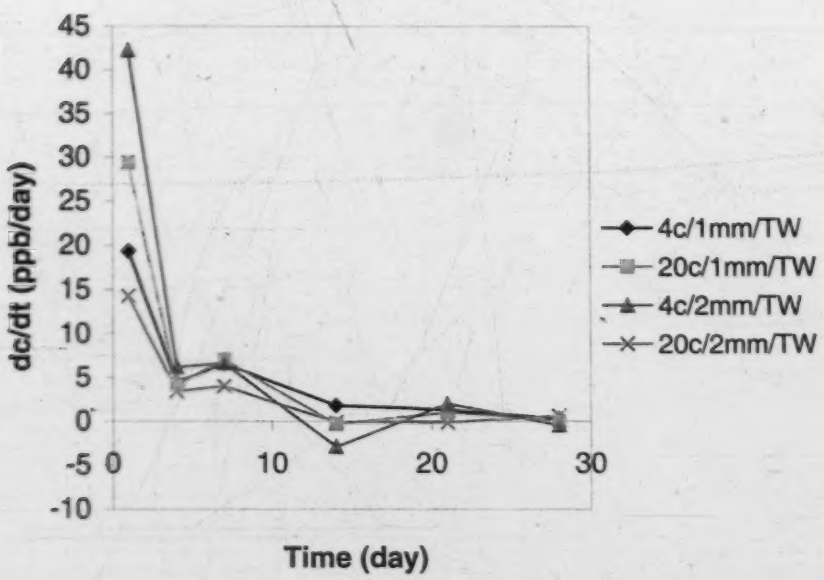


Figure 10. Trend of change in concentration with time for tap water samples

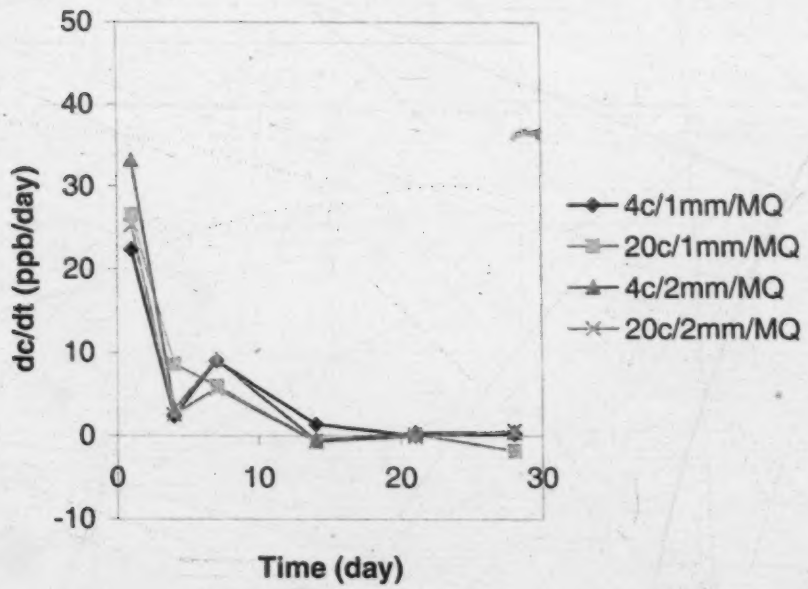


Figure 11. Trend of change in concentration with time for Milli-Q water samples

The differences in experimental conditions between the two studies will be useful in comparing the results. The present study was conducted with zero headspace to maximise retention of volatile compounds in the liquid phase. The earlier study allowed for an open, static headspace as is normal in water tanks. The epoxy lining being tested in that occasion was a tank lining and not a pipe lining as in the present case. The earlier tests used epoxy-coated steel panels immersed in water and complete water changes were carried out every 48 hours. In this study, however, only small partial water changes, to the order of 3% of total volume were carried out. A complete water change at the end of the experiment showed a dramatic 78% decrease in leachate concentration.

The earlier study found that the rate of leaching of organic compounds from the epoxy lining decreased from 704 mg/m^2-day on the first day to about 33 mg/m^2-day on the 30th day. The leachates consisted mainly of solvents used as a vehicle for epoxy application, including methyl ketones, xylenes and toluene. The present study tested for methyl ketones and xylenes and did not find any significant quantities of these compounds. Similar to the case of the earlier study, the present study found the rate of toluene leaching to reduce from about 26 µg/day on the first day to less than 1 µg/day on the 28th day. In both cases, the leachate concentration was found to reduce by 95% for the same time period, with the coated surface area remaining constant in the present study. Thus we can conclude that the exponential decrease in toluene leaching is in good agreement with previously published research.

4.4 Water absorption tests

To study the long term effects qualitatively, the water absorption tests were conducted using sections of epoxy lining. Results of the water absorption tests showed the trend depicted in Figure 12. The water uptake was found to increase exponentially with time. Following Fick's law of diffusion, the uptake should have increased with the square root of time. Since the exponential trend provides a better fit with the data, it was decided to project the trend forward in time to predict water absorption in approximately one year. It is assumed that the mode of water absorption does not change during this time period, as commonly applied. Measurements were obtained up to 9 months to verify that the trend did not deviate from the exponential form. Figure 12 indicates the exponential trend displayed by the immersed epoxy material sections at 40 °C and room

temperature (RT). Each point represents the average value of water absorbed by duplicate epoxy material sections.

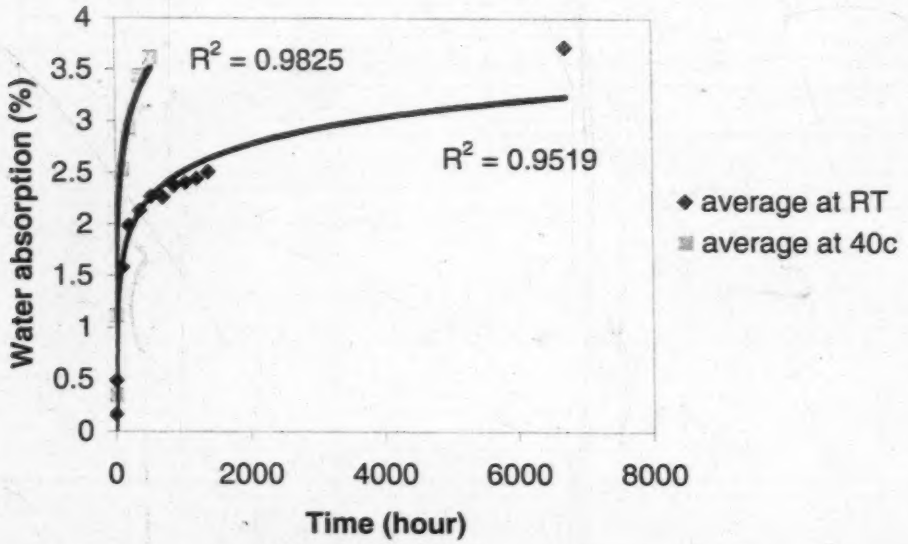


Figure 12. Trend of water absorption by epoxy lining material sections

It is seen in Figure 12 that the water absorption of the epoxy material sections is much higher at 40 °C than at room temperature. As discussed in the Materials and Methods, it is possible that the epoxy material at 40°C may have reached or exceeded its T_g value. In that case, the properties exhibited at this temperature would not be representative of the epoxy material under normal conditions, but rather that of its plasticized state. The room temperature sections were tested until about 9 months (6720 hours), and the final weight measurement recorded at the end of this period. From Figure 10, the final reading seems a little higher than the water absorption trend exhibited until then, but still follows the exponential curve.

The exponential water absorption trend obtained until 9 months with room temperature water was used to generate a possible value of water absorbed in about one

year (13 months or 10,000 hours). The forecast was restricted to one log unit of time, beyond which it would be unreasonable and inaccurate to predict the water absorption trend. For 13 months, water absorption is forecasted as 3.25%, corresponding to the log time of 4 in Figure 13.

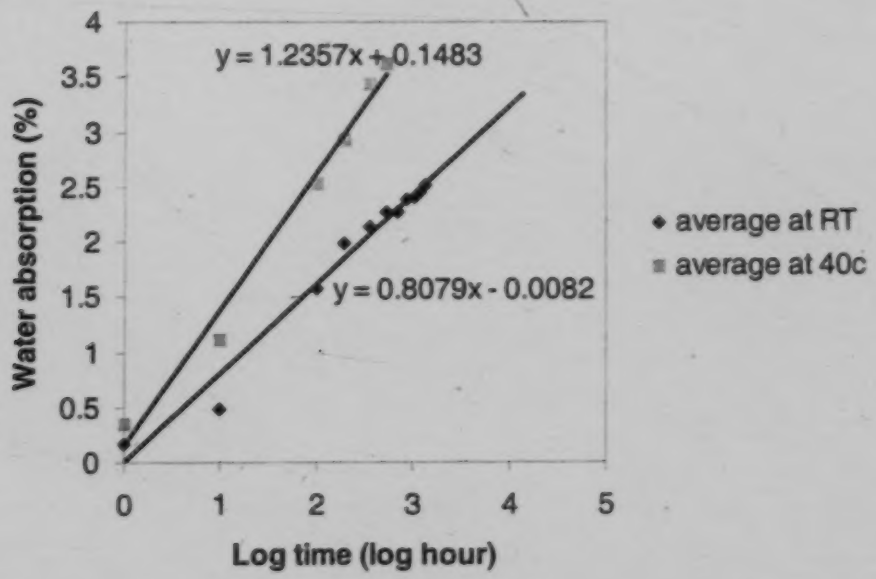


Figure 13. Exponential extrapolation of water absorption with time

FOSROC Inc, the manufacturer of the epoxy lining material, details the results of a water absorption test following the same ASTM standard D570–98 (FOSROC, 1998). Comparison of the results obtained at the end of one month showed that the manufacturer had reported the absorption as 0.8% at 20 °C while the present study showed 2.26% at room temperature of 26 °C. The difference in water absorption values may be explained by the difference in temperatures maintained in the two studies. However, the present experiment provides a qualitative measure of the increase in water absorption by the epoxy resin with a small increase in temperature. Also, the water absorption seems to be maximum in the initial time period and levels out with time, as is evidenced by the water

absorption of 2.26% in one month and 3.25% in one year. Further study is definitely warranted in this area to understand long-term behaviour of the epoxy lining material.

5. Conclusions

(1) The epoxy lining sprayed at 2 mm (80 mils) thickness provided protection to the underlying corroded pipe, with pits of up to 3/4 in. diameter, from further deterioration under normal service conditions. This is seen from the ability of the exposed lining material in this diameter to withstand an internal water pressure of 120 psi for two hours.

(2) The lining at the standard 1 mm (40 mils) thickness was shown to protect corroded areas up to 1/4 in. diameter with 75% efficiency. At this thickness, the lining provided uniform coverage of the pipe walls, based on visual observation during the post-cure camera inspection, which would reduce the red water problems associated with corroded cast iron pipes.

(3) Due to the brittle nature of the cured epoxy, the lining material was not able to withstand the deflection angle of 2° at the pipe joints applied during the pressure tests.

(4) Field samples of drinking water met and surpassed the Canadian regulatory requirements.

(5) Toluene found in the bench tests was not present in any field water samples from customers' homes, indicating its removal during air-cure and subsequent flushing.

(6) The epoxy lining tested has proved to be a reasonably good rehabilitation system judging by its physical and chemical characteristics.

(7) Water absorption tests indicate that the water uptake by the lining was higher than that expected from the manufacturer's technical specifications.

6. Recommendations

(1) Long term pressure tests may be conducted to study changes over time in semi-structural strength characteristics of the epoxy lining material.

(2) Accelerated testing, that is exposure to conditions that accelerate degradation of the epoxy lining material, may be useful in making service life predictions.

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